JET PROPULSION

Journal of the

AMERICAN ROCKET SOCIETY

MAY 27 1957

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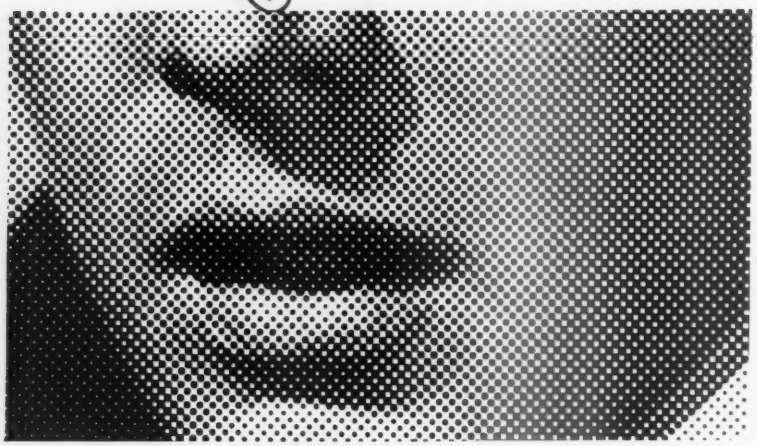
Atlantic Research Corp.



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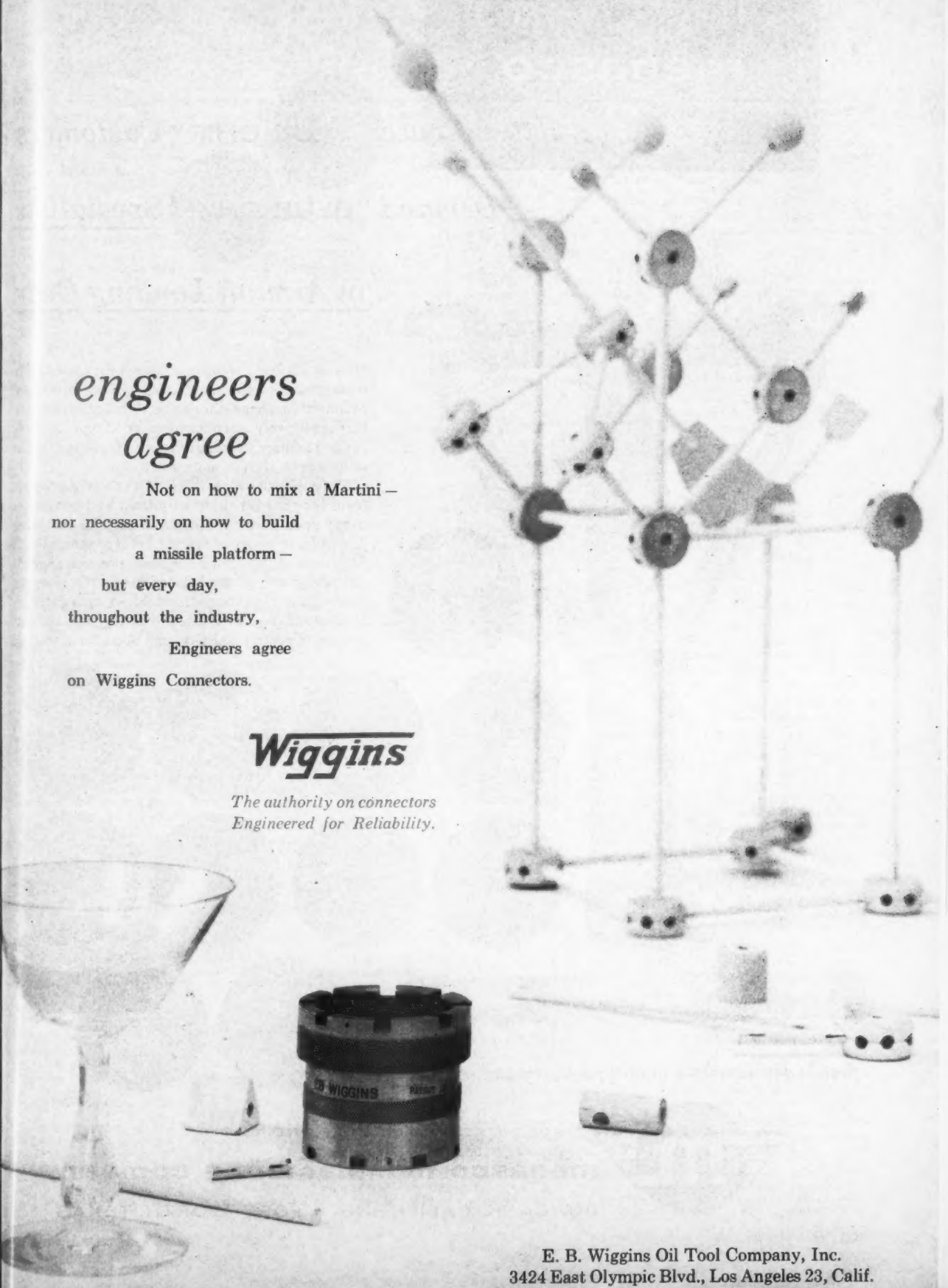

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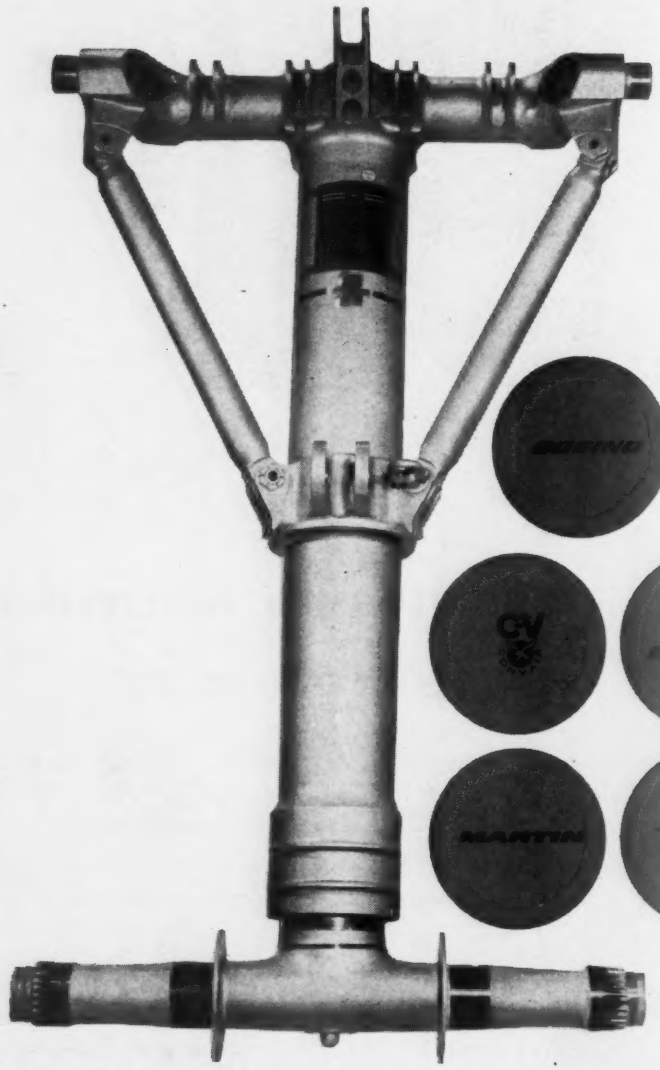

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JET PROPULSION, the Journal of the American Rocket Society, is devoted to the advancement of the field of jet propulsion through the publication of original papers disclosing new knowledge and new developments. The term "jet propulsion" as used herein is understood to embrace all engines that develop thrust by rearward discharge of a jet through a nozzle or duct; and thus it includes systems utilizing atmospheric air and underwater systems, as well as rocket engines. JET PROPULSION is open to contributions, either fundamental or applied, dealing with specialized aspects of jet and rocket propulsion, such as fuels and propellants, combustion, heat transfer, high temperature materials, mechanical design analyses, flight mechanics of jet-propelled vehicles, astronautics, and so forth. JET PROPULSION endeavors, also, to keep its subscribers informed of the affairs of the Society and of outstanding events in the rocket and jet propulsion field.

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Statements and opinions expressed in JET PROPULSION are to be understood as the individual expressions of the authors and do not necessarily reflect the views of the Editors or the Society.

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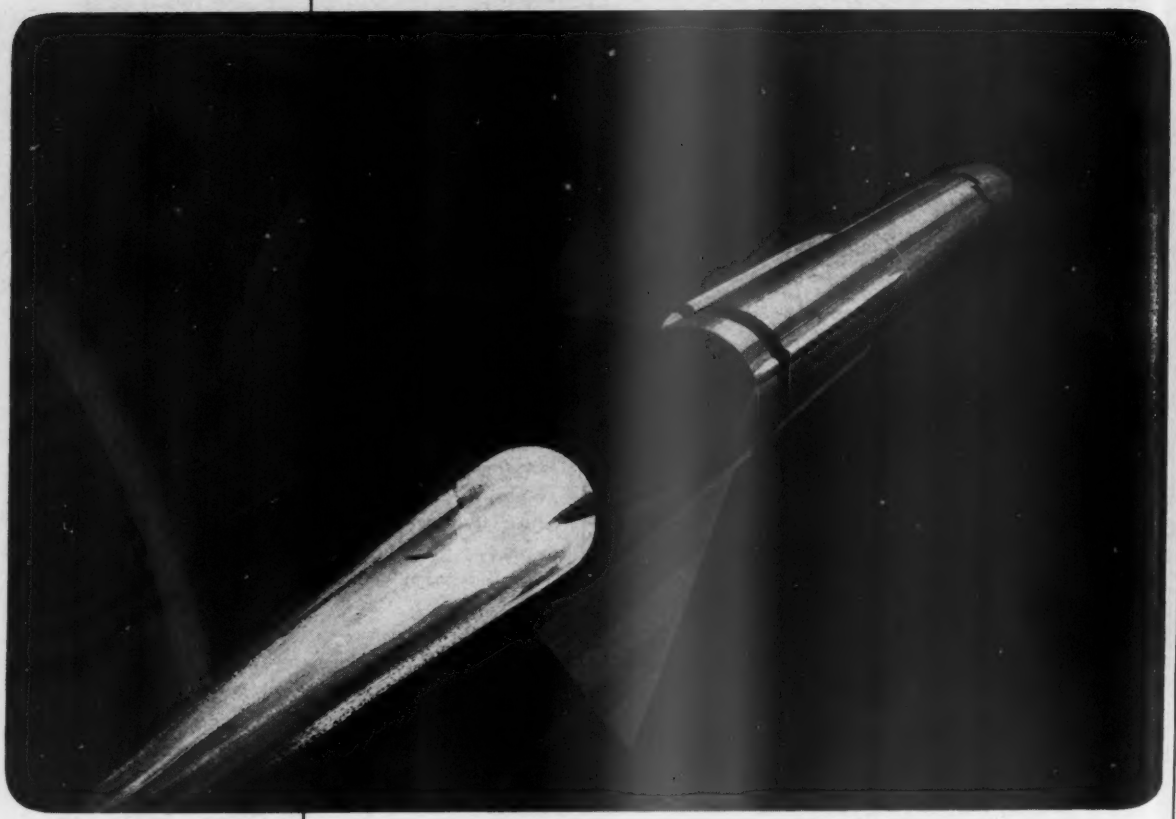

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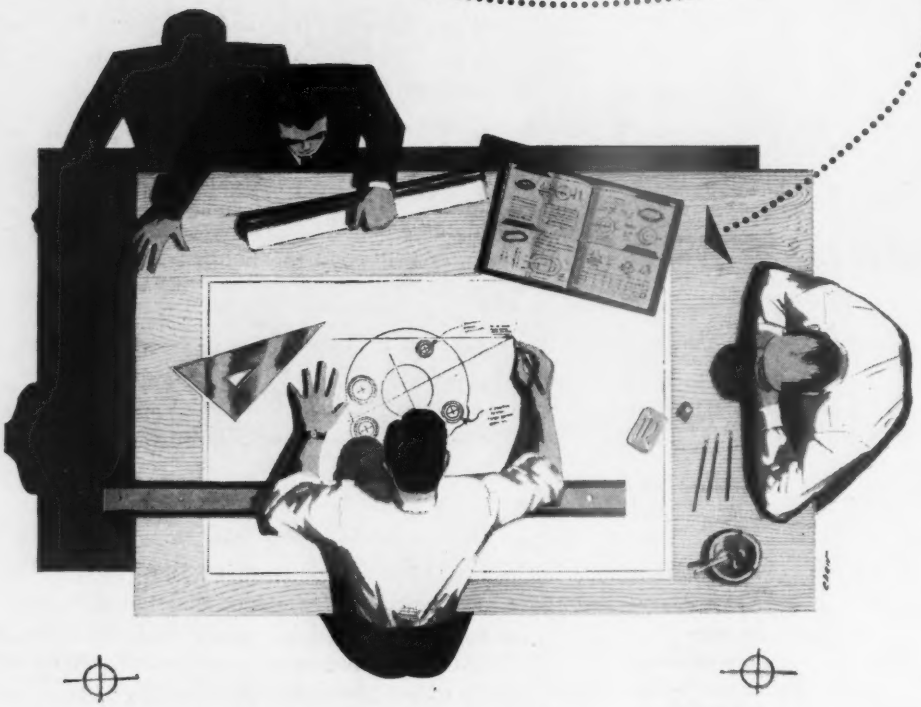

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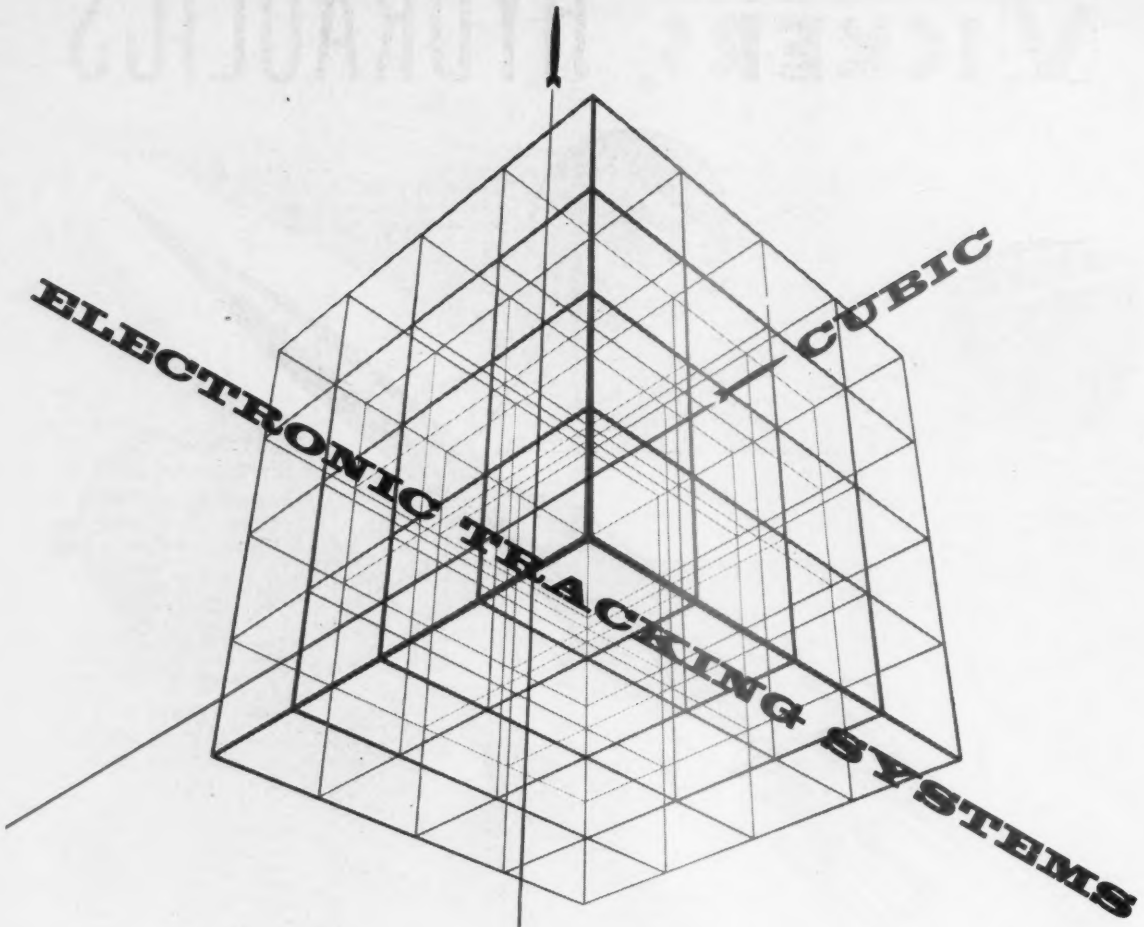

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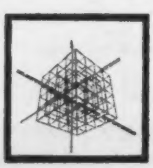

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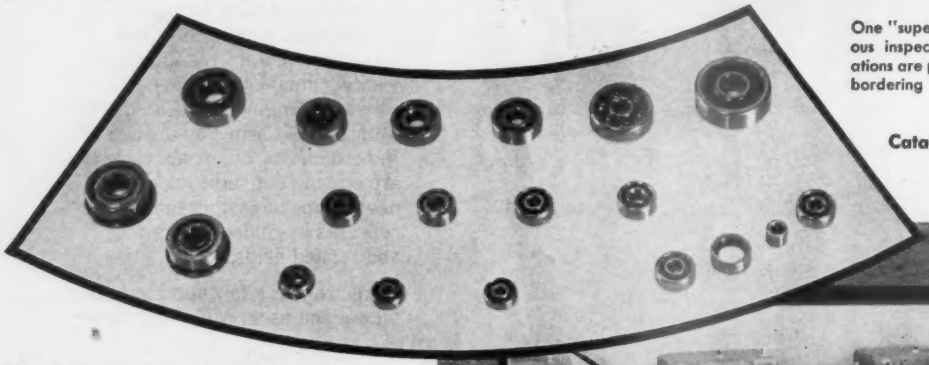

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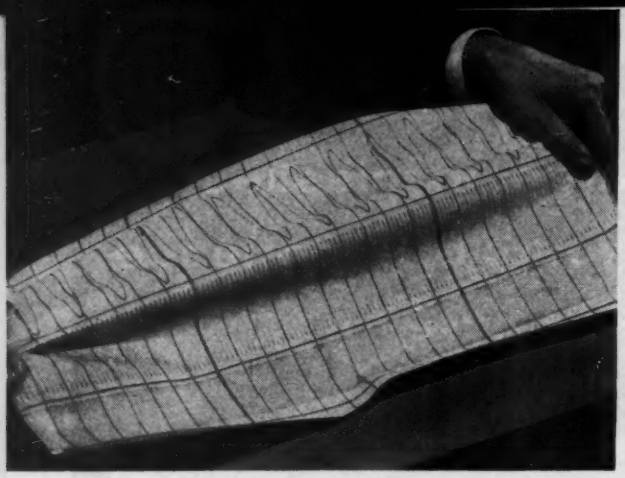

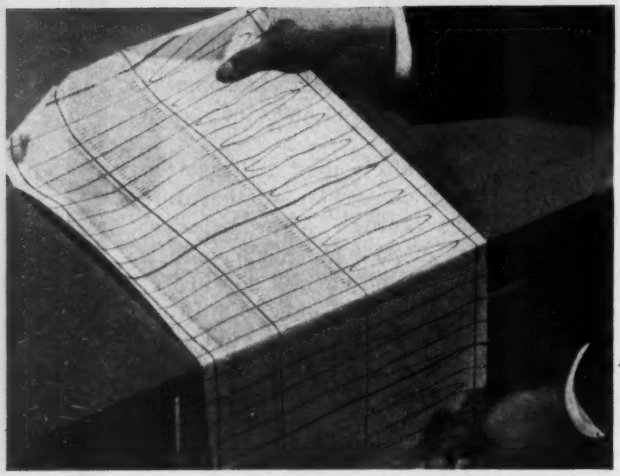

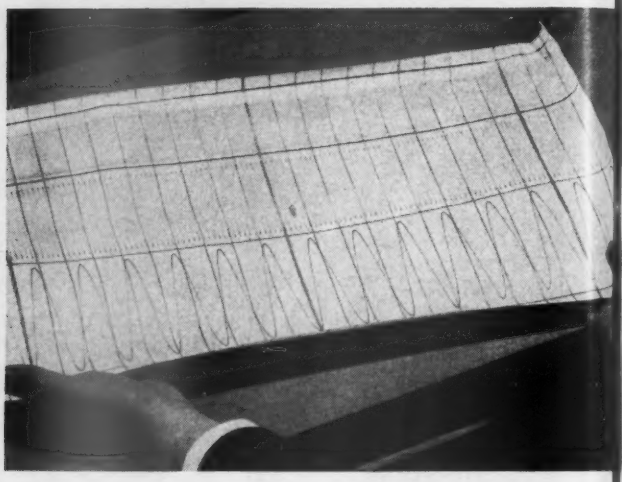

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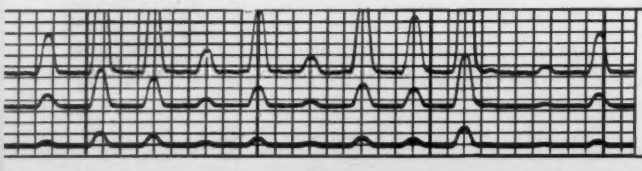

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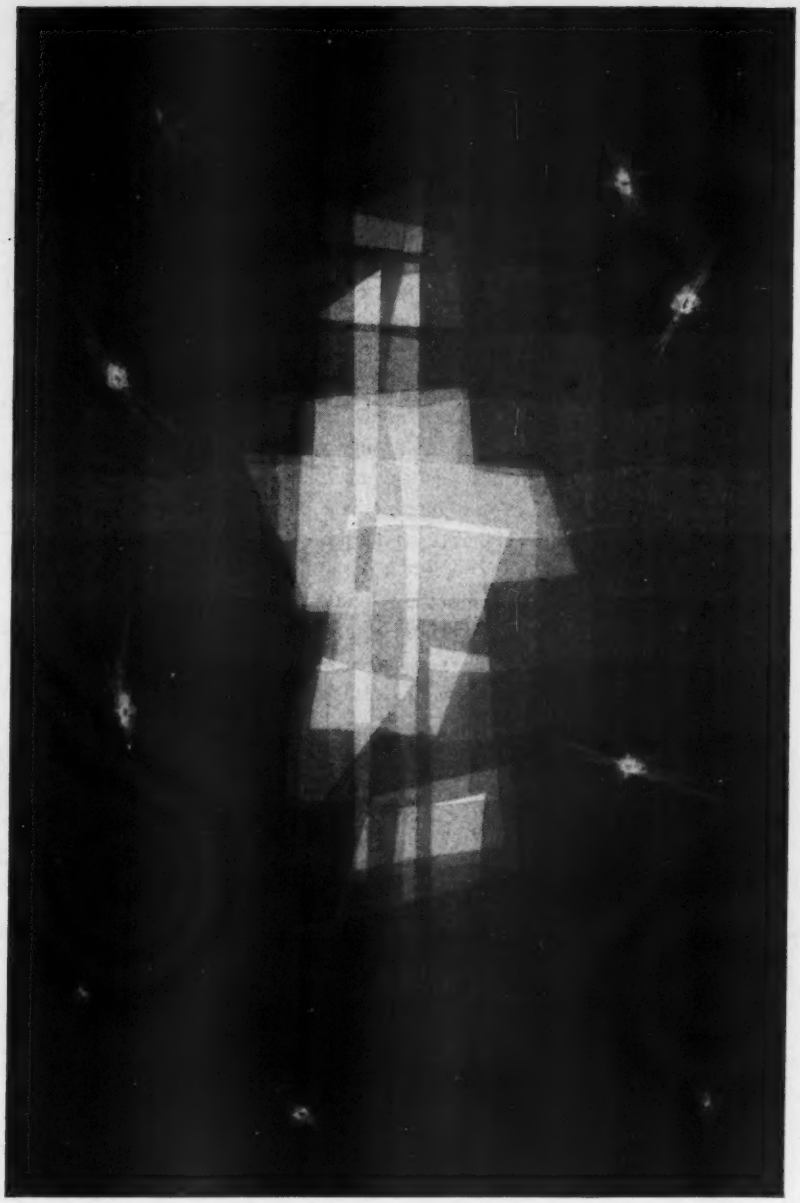

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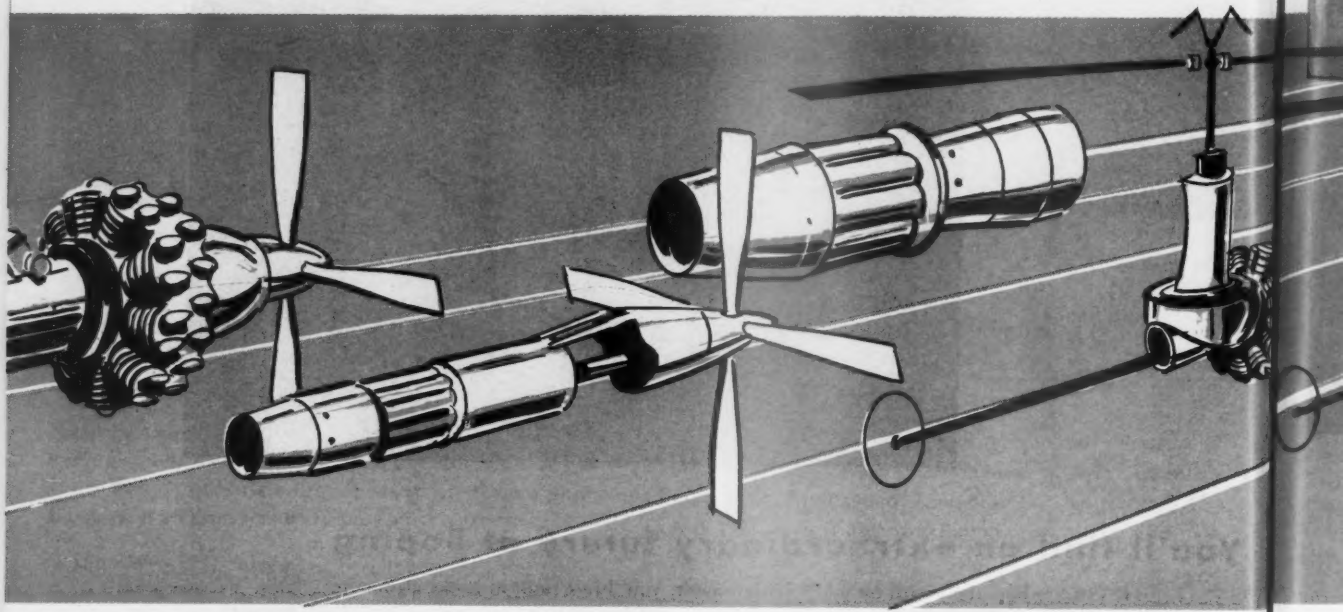

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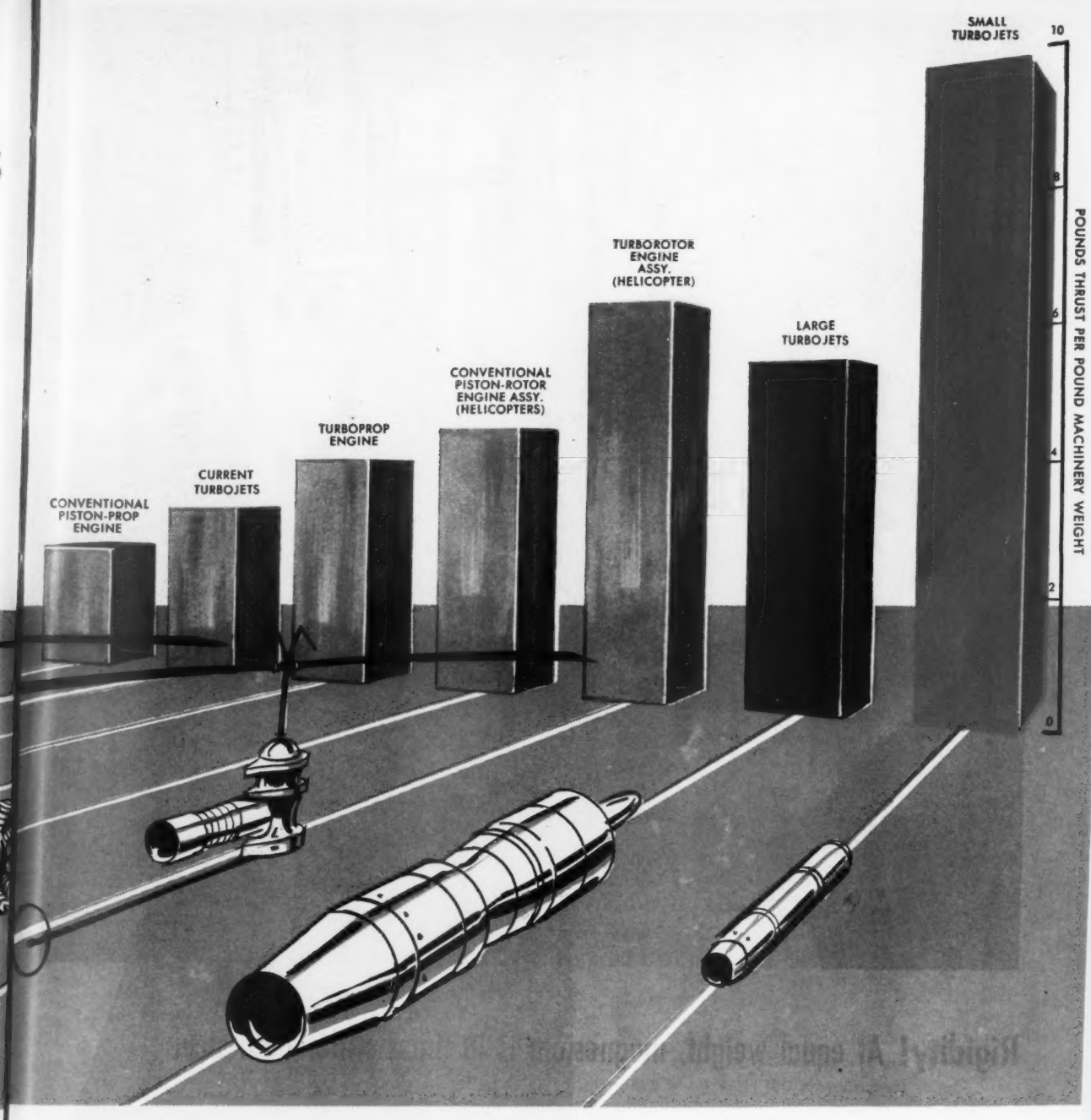

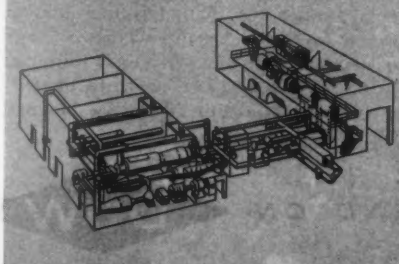

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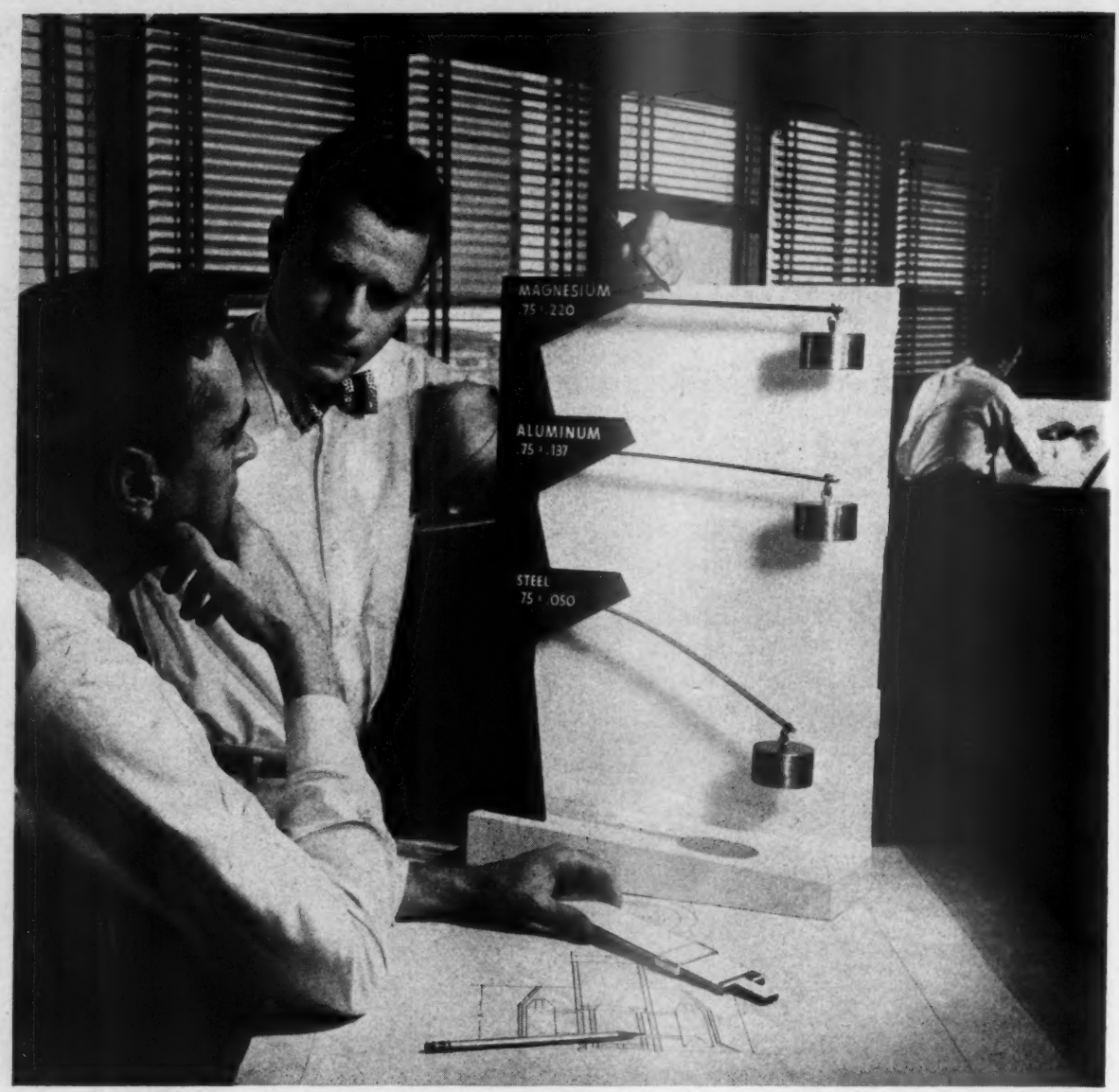

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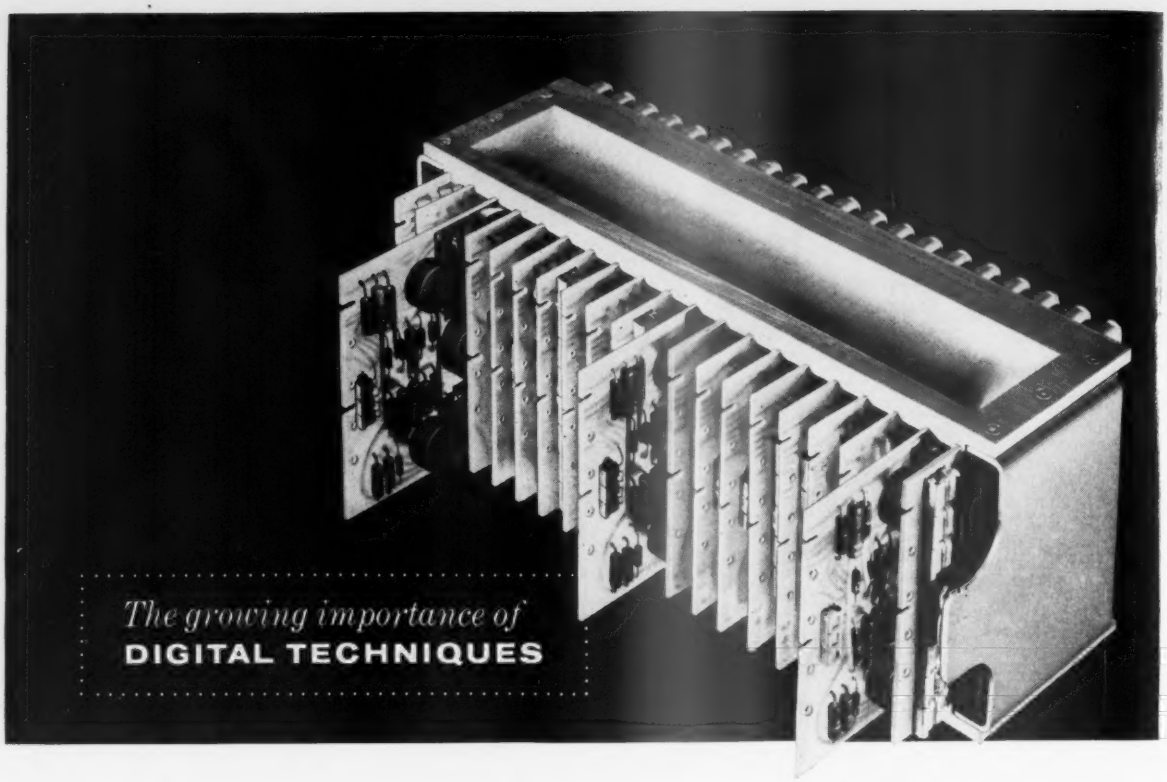

As recently as ten years ago it was just becoming evident that digital techniques in electronics were destined to create a new and rapidly growing field. Today, incorporated in electronic computers and other equipment, they constitute one of the most significant developments in scientific computation, in electronic data processing for business and industry, and in electronic control systems for the military. In the near future they are expected to become a major new factor in industrial process control systems.

The digital computer for scientific computation is becoming commonplace in research and development laboratories. Such machines range from small specialized units costing a few thousand dollars, to large general purpose computers costing over a million dollars. One of these large computers is a part of the Ramo-Wooldridge Computing Center, and a second such unit will be installed the latter part of this year. The digital computer has not only lightened the computation load for scientists and engineers, but has made possible many calculations which previously were impracticable. Such computers have played a major role in the modern systems engineering approach to complex problems.

Electronic data processing for business and industry is now well under way, based on earlier developments in electronic computers. Data processors have much in common with computers, including the utilization of digital techniques. In this field, teams of Ramo-Wooldridge specialists are providing consulting services to a variety of clients on the application of data processing equipment to their problems.

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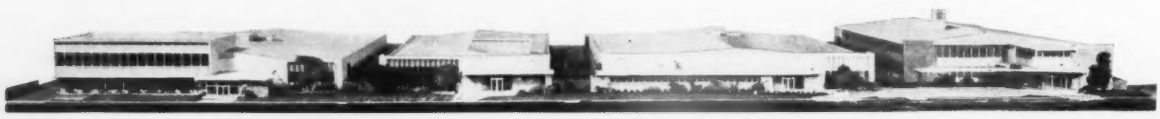

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Theoretical Considerations on Performance Characteristics of Solar Furnaces[1]

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The theoretical factors affecting the performance of the parabolic-type solar furnace are discussed. Calculations of the heat flux and the maximum temperature obtainable at the focus are presented for furnaces of different diameter-to-focal-length ratios. The analysis is extended to the California Institute of Technology lens-type furnace. The results indicate that a paraboloid of relatively low quality is capable of achieving temperatures over 2000 K. On the other hand, a research furnace capable of attaining temperatures in the range of 3600 to 4200 K would have to have a paraboloid of very high quality.

Introduction

IN THE course of an investigation into the feasibility of adapting a solar furnace for high temperature research on materials, it became apparent that a more basic understanding of the factors affecting its performance was necessary. Therefore, a theoretical analysis of its operation was undertaken to assist in predicting maximum attainable temperatures and heat fluxes for proposed solar furnaces, and to allow the evaluation of the performance characteristics of existing furnaces. The present paper is a report of this work.

Nomenclature

f = focal length of the paraboloid
D = diameter of the paraboloid at the edge
d = diameter of the circular image (sun image) in the focal plane produced by the central portion of the parabolic mirror
θ = angular aperture or rim angle of a parabolic reflector; angle between the axis and the line joining the focus to the edge of the paraboloid
p_o = solar constant measured above the atmosphere, 2 cal/min/sq cm
η_a = fraction of ideal solar constant which is available at the furnace site, taking into account losses through the atmosphere
η_r = reflectivity efficiency factor taking into account losses by reflectivity or absorptivity of the optical parts of the furnace
p_a = actual flux per unit area received at furnace site $p_a = \eta_a p_o$ (cal/min/sq cm)
P = total power or flux passing through the sun image
P' = total power or flux absorbed at the sun image
p = heat flux received per unit area within the sun image at the focus
p' = flux absorbed per unit area within the sun image
C = concentration ratio; $C = p/\eta_r p_a = p/\eta_a \eta_r p_o$
η_c = concentration efficiency; ratio of the total flux received within the sun image to the total flux which is received by the parabolic mirror
α = absorptivity coefficient
ϵ = emissivity coefficient
γ = index of geometrical perfection of a parabolic reflector; this index is given by the ratio of the actual measured flux within the sun image to the theoretical flux computed on the assumption that the paraboloid is geometrically perfect

General Discussion of the Parabolic-Type Solar Furnace

The most common type of solar furnace makes use of a reflecting parabolic mirror. When a parallel beam of light is received by such a mirror in a direction parallel to its axis, all the rays converge to the focal point of the paraboloid. Since the earth-to-sun distance is not infinite, the sun rays are not parallel, and the sun appears as a circular disk subtending an angle of about 32 min of arc.[6] For each point of the mirror, the incident and therefore the reflected beams are not single beams but cones with an apex angle of 32 min. When the axis of the paraboloid[7] is pointed toward the sun, the axis of the incident cone is parallel to the axis of the paraboloid, and the axis of the reflected cone passes through the focal point (see Fig. 1).

In order to obtain a sharp image of an object such as the sun or the moon, the parabolic mirror must have a long focal length with respect to its diameter. In Fig. 1 only the part of the mirror at the axis will form a circular image on a plane normal to the axis of the focus. The term "sun image" will be used to refer to this circular image. The reflected cones from other parts of the mirror will form ellipses since their axes

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[6] In the discussion to follow it will be assumed that this disk contributes to the flux uniformly over the entire surface. In actuality, the black body temperature is greater at the center and therefore it contributes more there than at the edges. As a result the flux in the sun image will not be quite uniform although it will average out as the calculated value.
[7] The terms paraboloid and parabolic mirror will be used interchangeably in this report.

cut the focal plane at angles other than 90 deg. The diameter d of the sun image depends only on the focal length f and is given by the simple formula

$$d = 2f \tan 16' = \frac{f}{107.3} \quad \ldots\ldots [1]$$

In the construction of solar furnaces, the reflecting paraboloid should have the largest diameter which is practical with respect to its focal length, when the purpose is to collect as much as possible of the incident radiation and concentrate it into the smallest possible area, i.e., the sun image in the focal plane. The various factors limiting the degree of concentration of energy and consequently limiting the maximum attainable temperature are discussed in detail in this report. Some of these factors have been considered previously by Trombe (4),[8] Cabannes (1) and Farber (2) and their coworkers.

Maximum Heat Flux at the Focus

Referring to Fig. 1, a cone of rays falling on an element of the parabolic mirror at point B is reflected as a cone having the same angle as that for the subtended sun, or about 32 min of arc. If θ is the angle AFB, it is apparent that the angle of incidence of the axis of the cone with the normal on the element of the mirror at B is $\theta/2$. The intersection of the reflected cone with the focal plane is then an ellipse. The major axis of the ellipse increases with the azimuthal angle θ and with ρ of the mirror element, and the minor axis increases directly with ρ.[9] This means that the outer portions of the mirror cast longer and wider ellipses around the sun image.

The energy per unit time which is concentrated within the sun image area will be called the power. This power can be obtained by integrating the contributions of all the elements of the mirror over its entire surface. Only a fraction of the power reflected by a circular ring element of differential width at an azimuthal angle θ and a distance ρ away from the focal point falls within the area of the sun image. This fraction is the ratio between the area of the sun image $\pi(f/214.6)^2$ and the area of the ellipse resulting from the intersection of the cone originating at a point of azimuthal angle θ with the focal plane, namely $\pi(\rho/214.6)^2(1/\cos\theta)$.[9] Hence the contribution of a ring at azimuthal angle θ to the area of the sun image is $(f/\rho)^2 \cos\theta$. The power reflected from a ring element of area ΔS is equal to the product of the solar constant p_o and the reduced area of the ring element corresponding to normal incidence $\Delta S \cos(\theta/2)$, or $p_o \Delta S \cos(\theta/2)$. The solar constant p_o is defined as the total solar radiation at normal incidence outside the atmosphere and has a value of about 2 cal/min/sq cm (3). The power contributed from the ring element to the sun image is therefore

$$\Delta P = \left(\frac{f^2}{\rho^2}\cos\theta\right)\left(p_0 \Delta S \cos\frac{\theta}{2}\right)$$

or

$$\Delta P = p_0 \frac{f^2}{\rho^2}\cos\theta\cos\frac{\theta}{2}\,\Delta S \quad \ldots\ldots [2]$$

The area of a concentric ring is

$$\Delta S = 2\pi\rho \sin\theta[(\Delta\rho)^2 + \rho^2(\Delta\theta)^2]^{1/2}$$

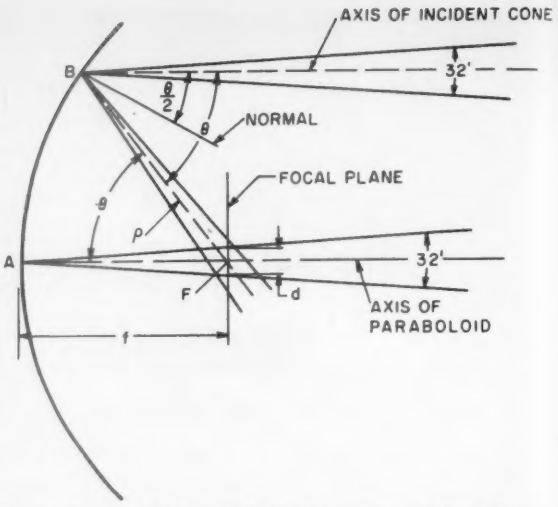

Fig. 1 Parabolic mirror with incident cone of rays being reflected to focal plane

From the geometry of the parabola

$$\rho = \frac{2f}{1 + \cos\theta}$$

and hence

$$\frac{1}{\rho}\frac{\Delta\rho}{\Delta\theta} = \tan\frac{\theta}{2}$$

As a consequence

$$\Delta S = 2\pi\rho^2 \sin\theta \sec\frac{\theta}{2}\,\Delta\theta \quad \ldots\ldots [3]$$

Combining Equations [2 and 3] and changing from differences to differentials

$$dP = 2\pi p_o f^2 \sin\theta\cos\theta\, d\theta \quad \ldots\ldots [4]$$

This expression is the power contributed to the sun image area by a differential ring at azimuthal angle θ. For the entire mirror, the total power within the sun image is obtained by integrating Equation [4]. Assuming that the central portion of the mirror up to an azimuthal angle equal to θ_1 does not reflect any rays[10] and that the maximum angular aperture of the mirror is θ_2, the total available power passing through the sun image is given by

$$P = \pi p_o f^2 (\sin^2\theta_2 - \sin^2\theta_1) \quad \ldots\ldots [5a]$$

If $\theta_1 = 0$ and $\theta_2 = \theta$, this expression becomes

$$P = \pi p_o f^2 \sin^2\theta \quad \ldots\ldots [6]$$

so that Equations [5a] can also be written as a difference in terms of Equation [6]

$$P = P_2 - P_1 = \pi p_o f^2 \sin^2\theta_2 - \pi p_o f^2 \sin^2\theta_1 \quad \ldots\ldots [5b]$$

In the derivation of Equations [5, 6] it has been assumed that all of the energy available before passing through the atmosphere is received by the mirror and is reflected without loss. This is, of course, practically impossible, and the power given by Equation [5 or 6] must be multiplied by a reflectivity factor less than unity which is characteristic of the material from which the reflecting surface is made and by an absorption factor. If the furnace has several reflecting surfaces (such as the case in which a flat mirror is used for tracking the sun) or has a combination of lenses and reflecting mirrors, a single coefficient less than unity may be used to take all the

[8] Numbers in parentheses indicate References at end of paper.

[9] Speaking exactly, the major semi-axis is given by

$$\left(\frac{\rho}{214.6}\right)\left(\frac{1}{\cos\theta}\right) \times \left[\left\{\frac{\sin(90° - 16')}{\sin(90° + 16' - \theta)} + \frac{\sin(90° + 16')}{\sin(90° - 16' - \theta)}\right\}\left(\frac{\cos\theta}{2}\right)\right].$$

The term in brackets is essentially unity at low values of θ, becoming 1.01 at a θ of about 87.5 deg. The minor axis has an even smaller error than this.

[10] This is generally the case since, when an object is placed at the focus, it casts a shadow on the mirror.

refractive or reflective losses into account. This coefficient will be designated by η_r.

The other factor η_a will be used to represent the fraction of the solar constant which is available at the furnace site. Thus the actual flux received at the furnace site p_a is equal to $\eta_a p_o$, where η_a takes into account losses due to atmospheric absorption and scattering.[11] With these efficiency factors, Equations [5, 6] may be written

$$P = \pi \eta_a \eta_r p_o f^2 (\sin^2 \theta_2 - \sin^2 \theta_1) \quad [7]$$

and

$$P = \pi \eta_a \eta_r p_o f^2 \sin^2 \theta \quad [8]$$

Equations [7, 8] represent what might be called the potentially available power passing through the sun image at the focus. When the radiation is to be used for heating a solid body, both the shape and the absorptivity (or reflectivity) of this body will determine how much of the potentially available energy is absorbed by the solid.

In discussing solar furnace performances it is more useful to consider the heat flux per unit area rather than the flux within the sun image, since this quantity is independent of the size of the image. The heat flux or power per unit area, designated by p, is readily obtained since it is known that the sun image area is $\pi(f/214.6)^2$. From Equation [8] the heat flux per unit area within the sun image is given by

$$p = \eta_a \eta_r p_o (/214.6)^2 \sin^2 \theta$$

or

$$p = 46.1 \times 10^3 \eta_a \eta_r p_o \sin^2 \theta \quad [9]$$

Concentration Ratio

The concentration ratio is defined as the ratio of the heat flux at the sun image of a sun furnace to the actual flux received from the sun on the earth at normal incidence after reflection, both per unit area. The concentration ratio is thus the number by which the actual flux at the furnace site p_a, corrected for reflectivity losses, must be multiplied in order to obtain the flux at the sun image, and is a function of the mirror geometry alone.

From Equation [9] the concentration ratio which is $p/\eta_r p_a$ or $p/\eta_a \eta_r p_o$ is given by

$$C = \frac{p}{\eta_a \eta_r p_o} = 46.1 \times 10^3 \sin^2 \theta \quad [10]$$

Obviously the concentration ratio obtainable with a parabolic mirror increases with the aperture ratio (diameter over focal length).

Concentration Efficiency

Another useful parameter in evaluating the performance of a solar furnace is the concentration efficiency η_C. This efficiency is defined as the ratio of the power received within the sun image area to the total power reflected by the parabolic mirror. The concentration efficiency η_C is thus

$$\eta_C = \frac{P}{\eta_r p_a \pi (D^2/4)}$$

Substituting Equation [8] for the total power received by the sun image and $\eta_a p_o$ for p_a, η_C becomes

[11] It is important to mention here that the solar radiation of interest in solar furnace operation is the direct solar radiation received at normal incidence, without the diffused, so-called "sky radiation."

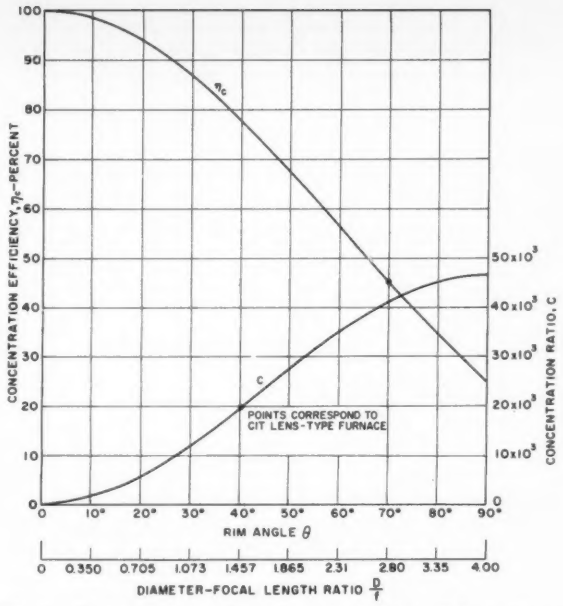

Fig. 2 Concentration ratio and concentration efficiency as a function of rim angle and diameter-focal length ratio for a parabolic solar furnace

$$\eta_C = \frac{\pi \eta_a \eta_r p_o f^2 \sin^2 \theta}{\eta_a \eta_r p_o \pi (D^2/4)}$$

or

$$\eta_C = \left(\frac{1 + \cos \theta}{2} \right)^2 \quad [11]$$

Curves showing the variation of concentration ratio and concentration efficiency with the azimuthal angle of the rim of the paraboloid and with the aperture ratio are given in Fig. 2. The relationship between the aperture ratio and azimuthal angle is given by

$$\frac{D}{f} = \frac{4 \sin \theta}{1 + \cos \theta}$$

Maximum Attainable Temperature

In order to speak about the temperature at the sun image of a solar furnace, it is necessary to describe the conditions under which this temperature is being created due to the presence of some kind of a solid body absorbing the radiation.

In the case of a cavity having an opening equal to that of the sun image, all of the flux will be used to raise the temperature inside the cavity. In this case the absorptivity coefficient α is considered to be unity and independent of θ. Equations [7, 8] therefore give the usable power in the case of a cavity.

When a flat plate is placed in the focal plane the absorptivity coefficient of the flat plate α must be taken into account. In this case α may be a constant less than unity, independent of θ. More often, however, α is some function of the incident angle of radiation θ. For a number of materials α is practically a constant for values of θ up to 60 deg and then decreases with increasing θ. In addition to considering the general case where $\alpha = \alpha_n F(\theta)$, the special case where $\alpha = \alpha_n \cos \theta$ will be treated in this report although no actual materials are known to have this exact behavior; α_n is the absorptivity coefficient for normal incidence.

For the general case where $\alpha = \alpha_n F(\theta)$, and introducing the factors η_a and η_r to correct for atmospheric absorption and reflectivity losses, Equation [4] must be rewritten as

$$dP' = 2\pi \eta_a \eta_r p_o f^2 \alpha_n F(\theta) \sin \theta \cos \theta \, d\theta \quad [12]$$

where the prime designation indicates absorbed power rather than available power. By integrating between θ_1 and θ_2 the total absorbed power within the sun image is given by

$$P' = 2\pi\eta_a\eta_r p_o f^2 \alpha_n \int_{\theta_1}^{\theta_2} F(\theta) \sin\theta \cos\theta \, d\theta \quad [13]$$

For the special case where $\alpha = \alpha_n \cos\theta$, Equation [12] must be rewritten as follows

$$dP' = 2\pi\eta_a\eta_r p_o f^2 \alpha_n \sin\theta \cos^2\theta \, d\theta \quad [14]$$

By integrating this equation between θ_1 and θ_2 the total absorbed power within the sun image is given by

$$P' = \frac{2}{3}\pi\eta_a\eta_r p_o f^2 \alpha_n (\cos^3\theta_1 - \cos^3\theta_2) \quad [15]$$

This relation simplifies to

$$P' = \frac{2}{3}\pi\eta_a\eta_r p_o f^2 \alpha_n (1 - \cos^3\theta) \quad [16]$$

in the case where $\theta_1 = 0$ and $\theta_2 = \theta$.

The flux absorbed per unit area within the sun image for a flat plate where $\alpha = \alpha_n F(\theta)$, from Equation [13] is given by

$$p' = 2(214.6)^2\eta_a\eta_r p_o \alpha_n \int_{\theta_1}^{\theta_2} F(\theta) \sin\theta \cos\theta \, d\theta$$

or

$$p' = 92.2 \times 10^3\eta_a\eta_r p_o \alpha_n \int_{\theta_1}^{\theta_2} F(\theta) \sin\theta \cos\theta \, d\theta \quad [17]$$

and for a flat plate where $\alpha = \alpha_n \cos\theta$, from Equation [16] by

$$p' = \frac{2}{3}(214.6)^2\eta_a\eta_r p_o \alpha_n (1 - \cos^3\theta)$$

or

$$p' = 30.7 \times 10^3\eta_a\eta_r p_o \alpha_n (1 - \cos^3\theta) \quad [18]$$

In order to calculate the maximum attainable temperature, it is also necessary to know the conditions under which the flux is emitted by a body. Consider an element of solid surface dS placed at the sun image and perpendicular to the furnace axis. When equilibrium is reached, and assuming that there is no heat loss by conduction through the solid body or by convection away from the body, the net radiation loss of the element is equal to the heat flux received by the element.

Before equating these two heat fluxes, it is necessary to compute the flux emitted by a solid body at the focus. Referring to Fig. 3, the flux radiation in a given direction θ per unit area of source is denoted by dq. The radiation intensity i is defined as the flux radiation per unit solid angle $d\omega$, or $i = dq/d\omega$. The radiation intensity for a black body of unit area is given by the Lambert cosine law as

$$i_b = i_{bn} \cos\theta \quad [19]$$

where i_{bn} is the radiation intensity normal to the radiating surface, and $\cos\theta$ is the effective radiating area normal to the direction θ. The total heat radiated in all directions per unit area of surface per unit time, or the emissive power, for a black body is given by

$$e_b = \int_{\text{over hemisphere}} i_b \, d\omega \quad [20]$$

or

$$e_b = 2\pi i_{bn} \int_0^{\pi/2} \cos\vartheta \sin\theta \, d\theta$$

or

$$e_b = \pi i_{bn} \quad [21]$$

For a nonblack body the emissive power is given by

$$e = \epsilon e_b \quad [22]$$

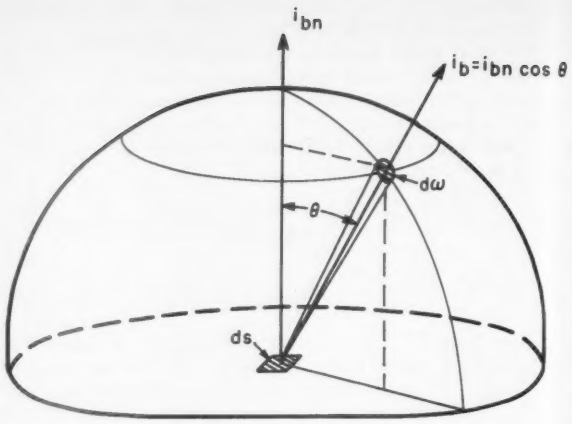

Fig. 3 Radiation intensity normal to the radiating surface in a given direction θ

where ϵ is the emissivity of the material and may be a function of θ.

The total heat radiation for a black body, given by Equation [21], is also equal to σT_m^4, where σ is the Stefan-Boltzmann constant and T_m is the temperature of the body; thus

$$e_b = \pi i_{bn} = \sigma T_m^4 \quad [23]$$

When the emissivity of the radiating body varies with θ, Equation [20] must be modified using the relationship $e = \epsilon e_b$ in order to obtain the total emissive power.

Thus, for any radiating body

$$e = \int_{\text{over hemisphere}} \epsilon i_b \, d\omega \quad [24]$$

For a body following the general equation $\epsilon = \epsilon_n F(\theta)$ in which ϵ_n is the emissivity normal to the radiating surface, the emissive power becomes

$$e = \int_{\text{over hemisphere}} \epsilon_n F(\theta) i_{bn} \cos\theta \, d\omega$$

$$\epsilon = 2\pi\epsilon_n i_{bn} \int_0^{\pi/2} F(\theta) \cos\theta \sin\theta \, d\theta$$

or

$$e = 2\epsilon_n \sigma T_m^4 \int_0^{\pi/2} F(\theta) \cos\theta \sin\theta \, d\theta \quad [25]$$

For the special case where $\epsilon = \epsilon_n \cos\theta$, the emissive power is given as

$$e = \int_{\text{over hemisphere}} \epsilon_n \cos\theta i_{bn} \cos\theta \, d\omega$$

$$e = 2\pi\epsilon_n i_{bn} \int_0^{\pi/2} \cos^2\theta \sin\theta \, d\theta$$

or

$$e = \frac{2}{3}\epsilon_n \sigma T_m^4 \quad [26]$$

It is now possible to write equations expressing the steady-state condition that the heat flux absorbed by the solid body at the sun image is equal to the flux emitted by the body. Assuming that the body loses heat only by radiation and radiates to a surrounding temperature T_o, and making use of a result of Kirchhoff's law that $\alpha = \epsilon$, this heat balance is expressed as follows.

For a cavity receiver:

$$p = \sigma(T_m^4 - T_o^4)$$

where

$$p = 46.1 \times 10^3\eta_a\eta_r p_o \sin^2\theta$$

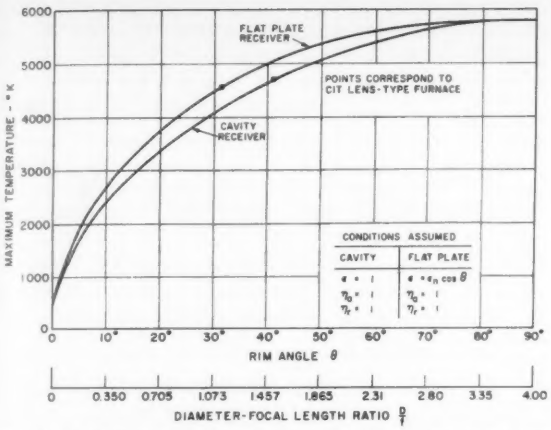

Fig. 4 Maximum temperature as a function of rim angle and diameter-focal length ratio for a parabolic solar furnace

For a flat receiver with an emissivity law of the general type $\epsilon = \epsilon_n F(\theta)$:

$$p' = 2\epsilon_n \left[\int_0^{\pi/2} F(\theta) \cos\theta \sin\theta \, d\theta\right] (T_m^4 - T_o^4)\sigma$$

where

$$p' = 92.2 \times 10^2 \eta_a \eta_r p_o \alpha_n \int_{\theta_1}^{\theta_2} F(\theta) \sin\theta \cos\theta \, d\theta$$

For a flat receiver following $\epsilon = \epsilon_n \cos\theta$:

$$p' = \frac{2}{3} \epsilon_n \sigma (T_m^4 - T_o^4)$$

where

$$p' = 30.7 \times 10^2 \eta_a \eta_r p_o \alpha_n (1 - \cos^3\theta)$$

Since the temperature of the receiver is generally very high compared with the ambient temperature, T_o^4 can be neglected as being very small compared with T_m^4 and the three equations above become

For a cavity where $\epsilon = 1$:

$$p = \sigma T_m^4 \quad \ldots\ldots [27]$$

For emissivity $\epsilon = \epsilon_n F(\theta)$:

$$p' = 2\epsilon_n \sigma T_m^4 \int_0^{\pi/2} F(\theta) \cos\theta \sin\theta \, d\theta \quad \ldots\ldots [28]$$

For emissivity $\epsilon = \epsilon_n \cos\theta$:

$$p' = \frac{2}{3} \epsilon_n \sigma T_m^4 \quad \ldots\ldots [29]$$

It is interesting to express the ratio p_o/σ in Equations [27–29] in terms of the temperature of the sun. The power radiated by the sun which has a radius R_s and a surface temperature T_s is $4\pi R_s^2 \sigma T_s^4$. The solar power flowing through a spherical surface $4\pi R_e^2$ concentric with the sun is $4\pi R_e^2 p_o$, R_e being the distance between the earth and sun. Equating these two solar powers, one obtains

$$4\pi R_s^2 \sigma T_s^4 = 4\pi R_e^2 p_o$$

and hence

$$\frac{p_o}{\sigma} = T_s^4 \frac{R_s^2}{R_e^2}$$

By using the known value of R_s/R_e or by using $p_o = 2$ cal/min/sq cm and $T_s = 5800$ K (3)

$$\frac{p_o}{\sigma} = \left[T_s \left(\frac{R_s}{R_e}\right)^{1/2}\right]^4 = \left(\frac{T_s}{14.65}\right)^4 \quad \ldots\ldots [30]$$

Combining Equation [30] with Equations [27, 28, 29], the maximum attainable temperatures in a solar furnace are given by the following equations.

For a cavity where $\epsilon = 1$:

$$T_m = \frac{T_s}{14.65} (\eta_a \eta_r C)^{1/4} \quad \ldots\ldots [31a]$$

or

$$T_m = T_s (\eta_a \eta_r)^{1/4} (\sin\theta)^{1/2} \quad \ldots\ldots [31b]$$

For emissivity $\epsilon = \epsilon_n F(\theta)$:

$$T_m = T_s \left[\eta_a \eta_r \frac{\int_0^{\theta} F(\theta) \sin\theta \cos\theta \, d\theta}{\int_0^{\pi/2} F(\theta) \sin\theta \cos\theta \, d\theta}\right]^{1/4} \quad \ldots\ldots [32]$$

For emissivity $\epsilon = \epsilon_n \cos\theta$:

$$T_m = T_s [\eta_a \eta_r (1 - \cos^3\theta)]^{1/4} \quad \ldots\ldots [33]$$

Computations have been carried out using Equations [31b, 33], taking $\eta_a = 1$ and $\eta_r = 1$. Curves showing the maximum temperature attainable in a parabolic furnace for the two types of receivers as a function of rim angle θ are presented in Fig. 4. Equation [32] also could be used to calculate T_m providing the function $F(\theta)$ can be defined.

A few remarks concerning the curves of Fig. 4 are in order. First, it might be surprising that for a parabolic mirror of rim angle equal to 90 deg a temperature equal to that of the sun can be reached. This result is a consequence of the fact that all conditions were idealized in the derivation of the formulas. The solar constant was taken equal to 2 cal/min/sq cm (which is the value measured in the stratosphere), the reflectivity of the mirror was assumed to be 100 per cent, the paraboloid was assumed to be optically perfect, and finally the body placed at the focus was taken as an ideal thermal insulator.

The assumption that the test specimen at the focus does not lose any heat through conduction or convection has little to do with the furnace itself and is a common problem in all types of calorimetric and temperature studies. The optical imperfections of the parabolic mirror will be reflected in the concentration efficiency and hence in the concentration ratio. In other words, the concentration efficiency and concentration ratio for actual furnaces will be represented by curves lying below those shown in Fig. 2. These curves can be obtained from experimental data only, and very few measurements have been made on existing solar furnaces and permit only an approximate picture of their performances. The two other factors responsible for lower temperatures than those given by the curves in Fig. 4 are the fraction of the ideal solar constant which is available at the furnace site, η_a, and the reflectivity of the mirror, η_r.

Comparison Between Cavity and Flat Plate Receivers

As shown in Fig. 4, a black body and a flat plate receiver, where $\epsilon = \epsilon_n \cos\theta$, reach the same maximum temperature if the rim angle of the furnace is 90 deg and under ideal conditions. It is interesting to note that when the rim angle is smaller than 90 deg the temperature reached by the flat plate receiver is higher than that of a cavity. Physically, this result may be explained as follows. In a cavity receiving the radiation over a cone angle of 2θ, the radiation emitted by the cavity is the same in all directions over a cone angle of 180 deg, as shown schematically in Fig. 5(a). For a flat plate subjected to the same radiant energy within a cone angle of 2θ, the emitted radiation varies as shown in Fig. 5(b) when $\epsilon = \epsilon_n \cos\theta$. Obviously the radiation losses through space outside of the cone of incident radiation are less for the flat plate than for the cavity.

Some general statements can be made in comparing the maximum temperatures of a cavity and a flat plate receiver

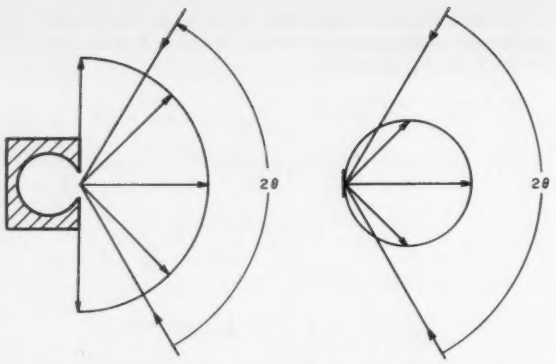

Fig. 5 Comparison between cavity and flat plate receivers

which would obey a general emissivity law of the type $\epsilon = \epsilon_n F(\theta)$. First, Equation [32] shows that the maximum temperature obtainable on the receiver is independent of the emissivity coefficient ϵ_n in the normal direction. Second, if the emissivity of the receiver decreases with increasing angle θ; i.e., if $F(\theta)$ decreases with θ, the flat plate receiver temperature is higher than that of the cavity. The contary is true if the emissivity increases with θ.

Effect of the Quality of the Reflecting Mirror

In the preceding sections it was assumed that the parabolic surface reflecting the sun rays was a geometrically perfect paraboloid. This is of course impossible to obtain, and the performances of any solar furnace will be less than those shown by the curves of Figs. 2 and 4. The geometrical imperfection of a parabolic mirror, i.e., unevenness of the mirror surface and its deviation from the correct profile, will reduce the actual concentration of the heat flux at the sun image. The index of geometrical perfection of a parabolic mirror γ may be defined as the quotient of the actual concentration ratio to the theoretical concentration ratio, i.e.

$$\gamma = \frac{C_{\text{actual}}}{C_{\text{theoretical}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots [34]$$

The value of γ can be estimated either by measurements of maximum temperature, if losses due to conduction and convection are slight, or by measurements of heat flux in a cavity at the sun image.

If the actual maximum temperature $T_{m\,\text{actual}}$ is measured, the value of γ may be obtained as follows. Using Equation [31a], the following relationship is obtained between the actual temperature $T_{m\,\text{actual}}$ and the actual concentration ratio C_{actual}

$$C_{\text{actual}} = \left(14.65\,\frac{T_{m\,\text{actual}}}{T_s}\right)^4 \frac{1}{\eta_a \eta_r} \quad \ldots\ldots\ldots [35]$$

The theoretical concentration ratio for a parabolic mirror of rim angle θ given by Equation [10] is

$$C_{\text{theoretical}} = 46.1 \times 10^3 \sin^2 \theta$$

Hence

$$\gamma = \frac{C_{\text{actual}}}{C_{\text{theoretical}}} = \frac{\left(14.65\,\dfrac{T_{m\,\text{actual}}}{T_s}\right)^4 \dfrac{1}{\eta_a \eta_r}}{46.1 \times 10^3 \sin^2 \theta}$$

or

$$\gamma = \left(\frac{T_{m\,\text{actual}}}{T_s}\right)^4 \frac{1}{\eta_a \eta_r \sin^2 \theta} \quad \ldots\ldots\ldots [36]$$

For example, consider a parabolic mirror with a rim angle of 60 deg and having a reflectivity of 0.85. If such a furnace produces a 4000 K cavity temperature[12] at the sun image when the solar radiation at the furnace site is 0.80 of solar constant, the index of geometrical perfection of the parabolic mirror is

$$\gamma = \left(\frac{4000}{5800}\right)^4 \frac{1}{(0.85 \times 0.8)\left(\dfrac{\sqrt{3}}{2}\right)^2} = 44\%$$

If the actual heat flux within the sun image is measured, instead of the temperature, the value of γ can be evaluated as follows. The actual flow is related to the actual concentration ratio by the equation

$$p_{\text{actual}} = \eta_a \eta_r p_o C_{\text{actual}}$$

and the theoretical heat flux is given by

$$p_{\text{theoretical}} = \eta_a \eta_r p_o C_{\text{theoretical}} = \eta_a \eta_r p_o\, 46.1 \times 10^3 \sin^2 \theta$$

Hence

$$\gamma = \frac{C_{\text{actual}}}{C_{\text{theoretical}}} = \frac{p_{\text{actual}}}{p_{\text{theoretical}}} = \frac{p_{\text{actual}}}{\eta_a \eta_r p_o\, 46.1 \times 10^3 \sin^2 \theta}$$

or

$$\gamma = \frac{p_{\text{actual}}\ (\text{cal/min/sq cm})}{92.2 \times 10^3 \eta_a \eta_r \sin^2 \theta} \quad \ldots\ldots\ldots\ldots [37]$$

From the point of view of determining the index of geometrical perfection of a parabolic mirror, Equations [36, 37] indicate that the method based on the heat flux measurement will result in a more accurate value of γ than that based on the maximum temperature measurement. Error in the temperature measurement will be magnified four times in the calculated value of the index of the geometrical perfection, while error in the heat flux measurement will be only directly reflected in the calculated value of γ. Equations [36, 37] show that for a given rim angle θ of a parabolic mirror and a given η_a and η_r, i.e., a known reduction in the solar constant and a known reflectivity of the parabolic mirror, the maximum actual temperature in a cavity is proportional to $\gamma^{1/4}$ and the actual heat flux received by a cavity is proportional to γ.

[12] The temperature of 4000 K may be considered as attainable in a solar furnace, although no reliable report has been made of any solar furnace in which such temperature has been reached.

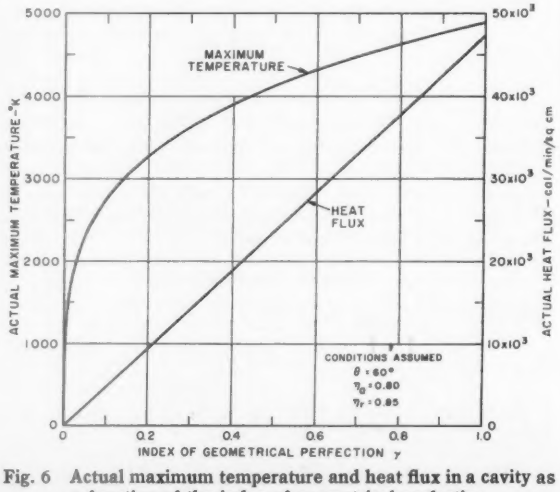

Fig. 6 Actual maximum temperature and heat flux in a cavity as a function of the index of geometrical perfection

A graphical representation of the variation of $T_{m\ actual}$ and p_{actual} with the index of geometrical perfection for a parabolic furnace operated under the conditions of reflectivity and solar transmission given in the example above is shown in Fig. 6. The temperature increases very rapidly with the index of geometrical perfection as expected from the T^4 law, while the heat flux increases linearly. As an example, a furnace with an index of geometrical perfection of 0.5 (which from a practical standpoint is probably an excellent paraboloid) would give 84 per cent of the theoretically attainable temperature of a perfect paraboloid, but the flux would reach only 50 per cent of the theoretical value. A furnace designed for maximum flux must therefore be much more accurately built than one intended for high temperature research only.

Factors Affecting Furnace Performance

The preceding discussion has indicated that three general types of factors affect the maximum temperature (or flux) that a solar furnace can achieve. All of these factors must be taken into account in any furnace design.

The first type is related to the optical geometry of the mirror, i.e., the aperture and focal length. Once these are chosen, then, regardless of the mirror location and construction, the image diameter, concentration ratio (or concentration efficiency) and the ideal maximum image flux and temperature are determined.

The second type includes those factors that reduce the performance of the furnace because of inefficiencies related to its construction and location. These are the atmospheric transmission coefficient (which includes the effects of site longitude, elevation and weather), the reflectivity coefficient, and the index of geometrical perfection of the paraboloid.

The last type involves those inefficiencies that the furnace target introduces. These would include the emissivity or absorptivity of the sample and the heat losses from the target by convection and conduction.

CIT Lens-Type Solar Furnace

The solar furnace at the California Institute of Technology is of the lens type. Nineteen lenses, 2 ft in diam with their axes pointed toward the sun, collect the energy over a total area of approximately 57 sq ft. These lenses are arranged in a hexagonal, close-packed array with one lens in the center, surrounded by six, and then twelve surrounding the central seven. Since all the images are to be superimposed, it is necessary to arrange a series of nineteen secondary lenses on a hemisphere centered at the focal point. The sun's converging rays are then brought to these lenses by eighteen oblique mirrors. The rays collected by the central lens do not have to be deflected, so do not require a mirror. The size of the sun's image in the focal plane, i.e., the equatorial plane of the hemisphere, is 0.5 in. in diam. The furnace is mounted like an astronomical telescope, with rotation around the earth axis and a declination axis. The focal point of the furnace is at the intersection of these two axes, so it remains fixed with respect to the ground when the furnace is tracking the sun. This tracking is achieved through a conventional astronomical drive and is automatic once the furnace has been pointed at the sun manually.

Concentration Efficiency

The concentration efficiency of the furnace, for a cavity receiver with an opening equal to the sun image, may be computed by adding up to the contributions of all lenses. As shown in Fig. 7, the nineteen secondary lenses are of four types, one center lens with $\theta = 0$, six inner lenses with $\theta_A = 46.2$ deg, six of twelve outer lenses with $\theta_B = 67.3$ deg and six of the same twelve with $\theta_C = 79.4$ deg. If the contribution of the center lens is taken as 1, the contribution of each type of lens is 1 times cos θ, in which θ is the azimuthal angle of each type. Therefore

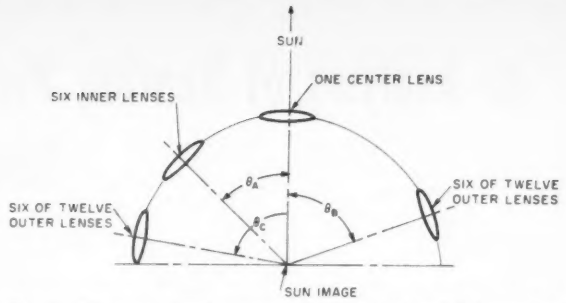

Fig. 7 Diagram showing arrangement of 19 small lenses on hemisphere

$$\eta_C = \Sigma \frac{\begin{pmatrix}\text{number of small}\\ \text{lenses}\end{pmatrix}\begin{pmatrix}\text{cosine of the corresponding}\\ \text{azimuthal angle of lens axis}\end{pmatrix}}{\text{total number of small lenses}}$$

and

$$\eta_C = \frac{1 + 6\cos\theta_A + 6\cos\theta_B + 6\cos\theta_C}{19}$$

$$\eta_C = \frac{1 + 4.15 + 2.32 + 1.1}{19} = 45\%$$

The relative contribution of each type of lens to the flux at the sun image is 1 for the center lens, 4.15 for the six inner lenses and 3.42 for the twelve outside lenses.

For a flat plate receiver following an absorptivity law $\alpha = \alpha_n \cos\theta$ the concentration ratio is given by

$$\eta_C' = \Sigma \frac{\begin{pmatrix}\text{number of small}\\ \text{lenses}\end{pmatrix}\begin{pmatrix}\text{cosine of the corresponding}\\ \text{azimuthal angle of lens axis}\end{pmatrix}^2}{\text{total number of small lenses}} \epsilon_n$$

or

$$\eta_C' = \epsilon_n \frac{1 + 6\cos^2\theta_A + 6\cos^2\theta_B + 6\cos^2\theta_C}{19} = 26.2\%\ \epsilon_n$$

and in this case the relative contribution of each type of lens is 1 for the center lens, 2.88 for the six inner lenses and 1.10 for the twelve outer lenses.

Concentration Ratio

The concentration ratio of the CIT furnace is calculated by multiplying the ratio of the collecting area, 57 sq ft, to the area of the sun image, $\frac{1}{4}\pi(\frac{1}{2}/12)^2$, by the concentration efficiency. Thus for a cavity receiver

$$C = 43{,}800\ \eta_C = 19.7 \times 10^3$$

and for a flat plate receiver where $\alpha = \alpha_n \cos\theta$, taking $\alpha_n = 1$

$$C' = 43{,}800\ \eta_C' = 11.5 \times 10^3$$

Maximum Attainable Temperature

The maximum attainable temperature for a cavity receiver may be computed using Equation [31a]. Assuming ideal conditions and no losses through the optical system, i.e., $\eta_a = 1$ and $\eta_r = 1$, T_m for a cavity receiver is 4700 K. For a flat

(Continued on page 546)

An Analysis of Heating Problems in Supersonic Ramjet Tailpipes

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For externally mounted supersonic ramjets, cooled principally by exposure to the surrounding free stream, heat transfer methods are used to predict temperatures attained by single-walled tailpipes during ground and air launch transients and at steady state conditions in the range of flight Mach numbers up to 4 and altitudes up to 100,000 ft. It is concluded that single-walled metal tailpipes, internally ceramic-coated where necessary, encounter a thermal barrier only in the high Mach number–low altitude region where more complex cooling means are required. A high performance variable-geometry "paper" ramjet was chosen as example, with internal gases at 4000 F throughout, near the maximum obtainable from hydrocarbon-air combustion. Graphs show how the tailpipe metal temperature at thermally critical locations is affected by the major variables of steady state flight conditions, ground and air launch transients, tailpipe exit geometry, wall thickness and wall material. Turbojet-afterburner tailpipes would experience the same thermal severity. Based on the analysis, engine size effects and thermal design factors for single-walled tailpipes are discussed. Also, a survey of more complex cooling systems is included. The heat transfer assumptions, methods and data employed in the analysis are contained in the Appendix.

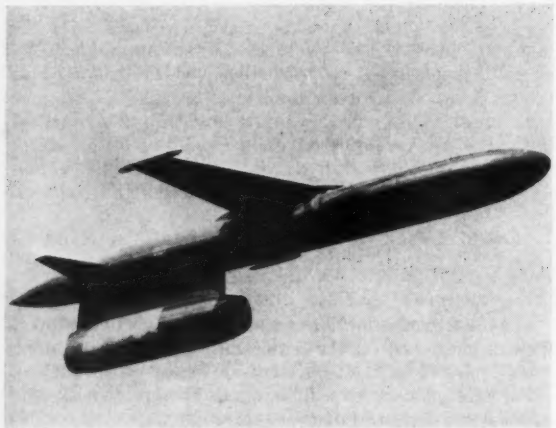

Fig. 1 20-in.-diam Marquardt XRJ-30-MA-8 subsonic ramjet on Martin KDM-1 target drone

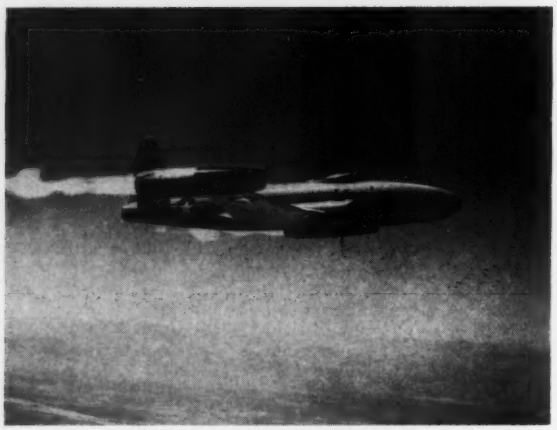

Fig. 2 Two 30-in.-diam Marquardt XRJ-31-MA-1 subsonic ramjets on Lockheed F-80

Nomenclature

C = coefficient
c = specific heat of solid, Btu/lb-°F
D = diameter of tailpipe at thermally critical plane (T.C.P.), ft
d = density of solid, lb/ft³
e = surface emissivity, dimensionless
G = weight flow per unit area, pps/ft²
g = acceleration due to gravity, 32.2 fps²
H = altitude above sea level, ft
h = heat transfer coefficient, Btu/hr-ft²-°F
k = thermal conductivity of solid, Btu/hr-ft-°F
M = Mach number, dimensionless
n = specific heat ratio, dimensionless
P = static pressure, psia
Q = heat flow per unit time per unit area, Btu/hr-ft²
T = temperature, °R
t = time, hr
W = weight flow rate, pps
x = wall thickness of solid, ft

Subscripts

a = ceramic coating
ah = ceramic hot face
c = convective
F = thrust
g = ramjet gas at T.C.P. (diameter D)
h = tailpipe hot inner surface ($= ah$ or mh)
m = metal
mc = metal cold face
mh = metal hot face
mm = metal mid-plane
n = net
o = flight, free stream or outside environs
r = radiant
t = total or stagnation

Presented at the ARS-ASME Aviation Division Conference, Los Angeles, Calif., March 14–16, 1956.

[1] Senior Thermodynamics Engineer.

Introduction

WHEN ramjet aircraft powerplants of circular cross section are mounted externally—underslung or on wing tips—practically the whole exterior surface is exposed to the free stream. Fig. 1 shows this for an installation of the Marquardt XRJ-30-MA-8 20-in.-diam subsonic ramjet on the Martin KDM-1 target drone, and Fig. 2 for two Marquardt XRJ-31-MA-1 30-in.-diam subsonic ramjets at the wing tips of a Lockheed F-80. Consequently, over-all design must consider both internal and external variables. A partial list of ramjet factors determining the flight performance of such a powerplant-vehicle combination includes internal and external geometry from inlet to exit, characteristics of fuel and burner systems, structural integrity and weight.

Since gas temperatures in ramjets may reach 4000 F for hydrocarbon fuels burning stoichiometrically, high temperature problems are built into the device, affecting structural and weight considerations strongly. In addition, aerodynamic heating becomes important with increasing supersonic flight speeds, e.g., flight total (or stagnation) temperatures T_{to} reach 1700 F for Mach 4 at sea level. The basic problem consists of keeping the temperatures of surfaces exposed to the internal hot gas and to the external free stream below structurally limiting values.

The forward surfaces of a supersonic ramjet are subject to aerodynamic heating only (from both inside and outside) which can generally be met, using high temperature metals if necessary. However, the tailpipe, in which combustion takes place, may exceed the structural temperature limit of such metals. Thus, the tailpipe of a ramjet is the component most likely to run into an ultimate thermal barrier, especially at tropospheric altitudes with their relatively high temperatures.

Thin-walled all-metal tailpipes directly exposed to full gas temperature on one side and to the free stream on the other side, may not overheat, although not otherwise cooled. Their use is, of course, very desirable, since weight is kept to a minimum and the entire air flow through the ramjet remains available for the combustion process.

It is the purpose of this paper to discover where a thermal barrier curtails the use of a single-walled tailpipe for circular ramjets by considering a variable-geometry ramjet engine during launch transients and at steady state conditions. Changes in tailpipe exit geometry, wall material and wall thickness will be evaluated, and more complex cooling means indicated where required.

It must be pointed out that the chief aim here is to present a general heat transfer approach to the tailpipe heating problem rather than an accurate analysis. The idealizations made and the particular example chosen reflect an attempt to demonstrate the basic effects; the numerical results should be regarded as comparative only.

Ramjet Parameters and Flight Conditions

In order to make the "paper" ramjet to be used for analysis representative of current and anticipated future practice, a range of flight speeds M_0 between Mach 1 and Mach 4 at altitudes H between sea level and 100,000 ft was selected. In order to be capable of a high performance level over this M_0 range, the paper ramjet was equipped with a variable inlet geometry. The assumed variation of inlet area with M_0 resulted in thrust performance superior to that of a fixed geometry engine having otherwise identical components. This is seen in Fig. 3 where net thrust coefficients for the two cases are plotted against M_0; both ramjets had the same exit size, with the fixed geometry engine optimized for Mach 3. Of course, the increased weight and complexity of variable geometry somewhat reduces the gain in over-all performance when expressed in terms of the thrust/weight ratio. The

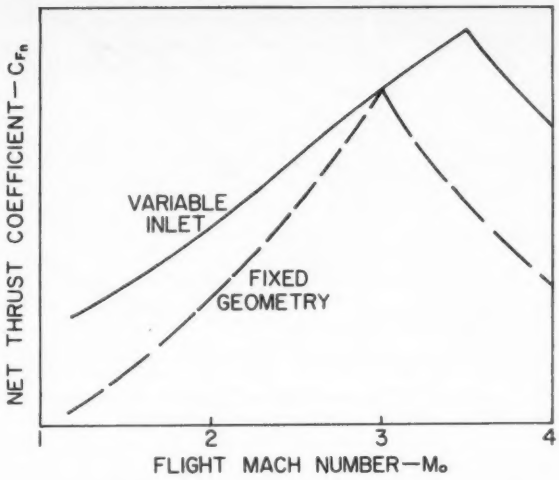

Fig. 3 Ramjet thrust characteristics

methods of (1 and 2)[2] were followed in the ramjet performance calculations.

The exit of the paper ramjet consisted of a 30-in.-diam single-walled tailpipe ending in a convergent-divergent nozzle. In this analysis two exit nozzle sizes were studied, with throat areas 50 and 100 per cent of the full tailpipe area. For the 50 per cent exit, with maximum hydrocarbon combustion gas temperature, the paper ramjet developed a net thrust of the order of 20,000 lb at Mach 3 and 30,000 ft, to give an idea of its capabilities.

It is well known that supersonic ramjets must be boosted by external power to a supersonic Mach number before they themselves can take over, i.e., produce enough thrust to accelerate under their own power. The launch transient undergone by a supersonic ramjet from rest up to its cruise point (at given M_0 and H) therefore generally consists of a rocket boost followed by self-acceleration. Overheating of tailpipes is possible during the ramjet-powered part of the transient, especially when the take-over altitude is low.

For the paper ramjet two plausible launch paths were formulated. In both cases the take-over speed was Mach 2 and the final cruise point Mach 4 at 100,000 ft To permit evaluation of the effect of take-over altitude, a "ground launch" value of 4000 ft and an "air launch" value of 40,000 ft were arbitrarily assumed, with a uniform climb rate of roughly 1200 fps for both transients. This resulted in a 50-sec air launch and an 80-sec ground launch path under ramjet power, corresponding to average resultant accelerations of about 1 g.

The gas (i.e., air plus fuel) weight flows W_g through the ramjet were based on the inlet area variation chosen, a specific heat ratio n of 1.4 for air and a fuel-air ratio of 0.07 (at maximum heat release). The same n was also used to find T_{to} values. Although calorific imperfections in the air make themselves felt as Mach number increases, they were considered small and not taken into account. One reference (3) places the actual value of total-to-static temperature ratio at Mach 4 and a T_{to} of 1700 F within 5 per cent of that obtained with $n = 1.4$.

Since only one inlet area variation with M_0 was assumed, the variation of W_g with M_0 and H was independent of exit nozzle throat area. This led to different thrust performance for 50 and 100 per cent exit nozzles, but allowed a better thermal comparison since W_g was eliminated as a tailpipe variable.

[2] Numbers in parentheses indicate References at end of paper.

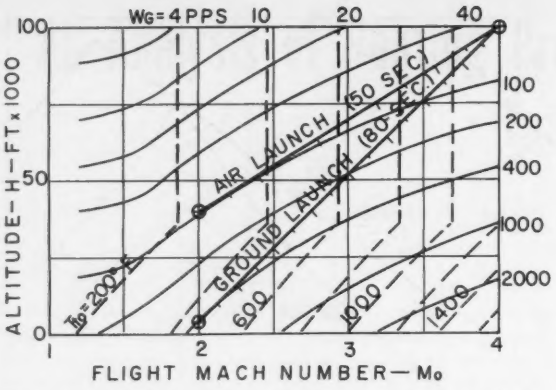

Fig. 4 Ramjet flight range and launch paths—W_g = ramjet gas flow, T_{to} = flight total temperature

Fig. 4 shows constant W_g and T_{to} lines for the paper ramjet on an M_0-H plot. This plot reflects the latest NACA Standard Atmosphere (4). It is seen that due to the extensive flight range and the variable inlet a 500-fold variation in gas flow occurs, from 4 to 2000 pps. Also shown in Fig. 4 are lines indicating the ground and air launch paths, with 5-sec intervals marked off on them. A plot of this kind is useful since the gas flow lines roughly correspond to levels of tailpipe heating, as will appear from Fig. 6. When lines representing transients—whether launches, dives or other maneuvers—are drawn on the plot, it may be seen at a glance what relative thermal severity is encountered along them, although the precise effects depend on the time scale associated with the transients.

Heat Transfer Treatment

The physical system under consideration was assumed to consist of a uniformly hot and fully turbulent gas inside the cylindrical tailpipe, with a fully turbulent air boundary layer on the outside. Heat transfer was postulated in a lateral direction only, by radiation and forced convection from the hot gas to the tailpipe inner surface, across the wall by conduction, and from the outer surface to the environs by radiation and forced convection.

In line with the declared purpose no special efforts were made to utilize data from the most recent literature. Instead, all heat transfer coefficients were based on the latest edition of (5), except that early experimental data by Eber (6) were used for external forced convection. Steady state wall temperatures were obtained by iterative solutions of the heat flow balances, while the transient cases were handled by step-wise numerical or graphical methods.

The Appendix contains detailed information regarding the assumptions, heat transfer coefficients, and steady state and transient methods. The numerical accuracy of the results was limited by the methods employed, so that temperatures may be considered to lie within 10 F of the quoted values in most cases.

Tailpipe Variables

Preliminary calculations showed that the most important factor determining tailpipe wall temperature was the convective heat transfer coefficient from the gas to the inner surface (h_{cg}). Since this varies inversely with (diameter)$^{1.8}$ for a given gas weight flow W_g (see Appendix, B), the smaller the diameter, the hotter the tailpipe becomes. Therefore, the plane of the exit nozzle throat was taken as the thermally critical plane (T. C. P.).

The hot gas total temperature at the T. C. P. (T_{tg}) was assumed to be uniform over the cross section and constant over the flight range at the value of 4000 F. For hydrocarbon-air mixtures the maximum ideal T_{tg} values obtainable lie in the range of 3600–4400 F as T_{to} increases from 0 to 1700 F (7). Thus, 4000 F represents an average maximum gas temperature over the flight range, assuming 100 per cent combustion efficiency. In this range the fuel-air ratio by weight at maximum combustion temperature averages 0.07. Since in practice combustion efficiency is always below 100 per cent, decreasing with altitude, and ramjets are only flown at maximum power for a limited time, this assumption corresponds to the highest possible internal thermal severity.

Three tailpipe configurations were investigated, as shown in Fig. 5. Tailpipe A had no contraction, i.e., a 100 per cent cylindrical nozzle; tailpipe B had a gradual taper down to a throat area of 50 per cent of the full tailpipe area, diverging more rapidly to the full area; tailpipe C remained cylindrical and then converged rapidly to a 50 per cent throat followed by a divergence identical to that in B. The h_{cg} influence discussed above implies that tailpipes B and C (with 50 per cent exit) would reach higher temperatures than tailpipe A (with 100 per cent exit) for the same W_g. Further, it was considered for the 50 per cent exits that the external air flow adhered to the gradually tapering tailpipe B, but separated from the nozzle contour of straight tailpipe C. Accordingly, the convective heat transfer coefficient from outer surface to free stream (h_{co}) was taken at the full flat plate value for tailpipes A and B, but arbitrarily at half that value for C. The foregoing suggests that tailpipe C should run hottest, followed by B and A, in that order.

The choice of exit nozzle shape, apart from thermal consideration, is primarily determined by internal (thrust-producing) and external (drag-producing) factors as they relate to the particular flight application. If low external drag is the principal requirement, the cylindrical (type C) is to be preferred to the tapered (type B) tailpipe for a given exit contraction. If only structural strength is important, the tapered tailpipe is to be preferred. Tailpipes with 100 per cent exists will produce more thrust than those with smaller throats, so that a type A tailpipe may be mandatory if high performance is desired. Ultimately, exit nozzles with continuously variable throat areas may be used, subject to different heating conditions as the shape changes.

Three tailpipe walls were analyzed to demonstrate effects due to thickness and material changes: (a) Thin metal wall, $^1/_{16}$ in. metal thickness; (b) thick metal wall, $^5/_{16}$ in. ($^1/_{16}$ + $^1/_4$) metal thickness; (c) thick composite wall, $^1/_{16}$-in. metal with $^1/_4$-in. internal ceramic coating.

The relative effectiveness of adding the same $^1/_4$-in. thickness of metal or ceramic to the thin metal wall could thus be

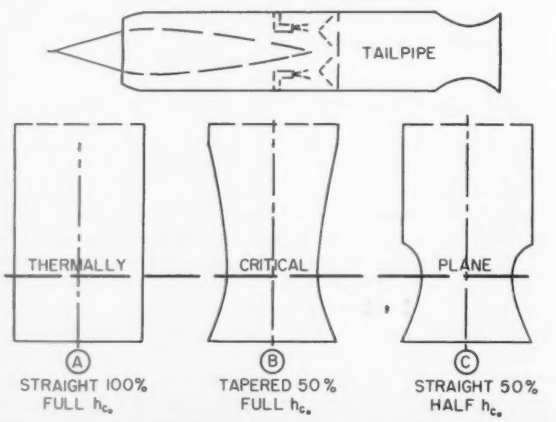

Fig. 5 Single-walled ramjet tailpipes

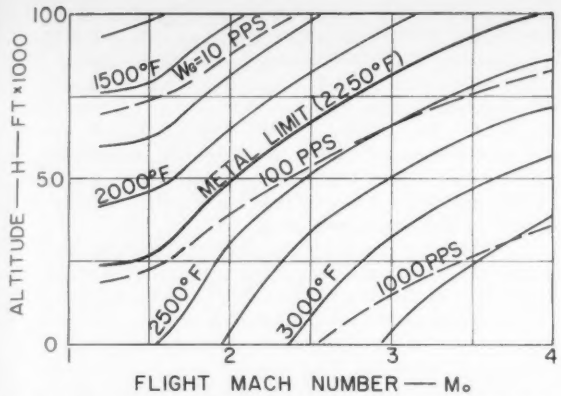

Fig. 6 **Steady state wall temperatures over ramjet flight range—tailpipe B, $\frac{1}{16}$-in. metal wall. 4000 F gas temperature—maximum power. Wall temperatures are lower at reduced power cruise**

determined. Although the added $\frac{1}{4}$-in. dimension might appear excessive, it brings out the effects more clearly and illustrates the use of thicker walls for cases of high thermal severity.

Based on a recent review of high temperature materials for powerplants (8), the heat transfer properties for the metal were taken as those of Haynes Stellite N-155, and for the ceramic as those of Norton Rokide A. The former is predominantly a chromium-nickel-cobalt alloy, the latter an aluminum oxide coating. Not necessarily in accord with the present state of the art, a constant structural temperature limit of 2250 F was assumed for the metal, a few hundred degrees below its melting point. Likewise, for the ceramic, it was assumed that a $\frac{1}{4}$-in. thickness of it could be bonded to the metal, remaining intact up to 3500 F. Roughly, the ceramic had a thermal conductivity $\frac{1}{10}$, a thermal diffusivity $\frac{1}{4}$, and a density $\frac{1}{3}$ those of the metal.

Preliminary calculations showed that for the thin $\frac{1}{16}$-in. metal tailpipe the temperature differences across the wall were of the order of only 30 F. Therefore, for all cases involving it, temperature gradients were neglected and a single wall temperature was calculated. For the $\frac{5}{16}$-in. metal wall, however, the gradient was considered and both "hot face" and "mid-plane" temperatures were computed. Temperature gradients were taken into account for the composite wall, but no ceramic temperatures were evaluated since with the assumed 3500 F limit no overheating was indicated.

Single-Walled Tailpipe Temperatures

Steady State Results

Steady state temperatures were calculated throughout the range of flight conditions for tailpipe B (intermediate severity) at the thermally critical plane for the thin $\frac{1}{16}$-in. metal wall. Here "steady state" refers to the temperature equilibrium reached after a sufficiently long level flight at a given Mach number and altitude. Fig. 6 shows the results in the form of solid lines of constant wall temperature on the M_0-H grid. For comparison some constant W_g lines are drawn dashed, showing that the ramjet gas flow is a relative measure of tailpipe temperature. This might be expected since, other things being equal, h_{cg} is the prime influence on wall temperature.

The temperatures are seen to vary from 1250 F to well over 3000 F, with the limiting metal temperature of 2250 F constituting the applicable thermal barrier. The thermally safe zone lies to the left of the limit line and above it, in this case above 50,000 ft at Mach 2; above 80,000 ft at Mach 3; and above 100,000 ft at Mach 4. It must be remembered that this thermal barrier reflects maximum power operation; the reduced power needed for steady state cruise will result in lower wall temperatures and a thermally safe zone down to lower altitudes.

The same qualification applies to Fig. 7 where lines similar to those in Fig. 6 are determined for tailpipes A and C. The solid lines compare the 2250 F metal limit for all three configurations. The thermal barrier is pushed back considerably when going from B to A, but becomes a little more severe when going from B to C. The temperature differences between B and C are of the order of 100 F or less, while those between B and A run up to several hundred degrees. Such comparisons assist in over-all design procedures when a choice must be made between exit nozzles which differ in shape and contraction ratio.

The discontinuous lines on Fig. 7 show the steady state effects of wall thickness and material changes on the 2250 F limit with tailpipe B. The hot face of the thick $\frac{5}{16}$-in. metal wall represents more severity than the thin $\frac{1}{16}$-in. wall, although the $\frac{5}{16}$-in. mid-plane line is less severe.

These effects are consequences of increasing the thermal resistance of the wall by adding metal thickness. In the practical case the mid-plane temperature could be considered the one of structural consequence, since it determines the strength of the wall, provided that the hot face is not near the melting point. The differences between the $\frac{1}{16}$-in. and the $\frac{5}{16}$-in. mid-plane temperatures at fixed flight conditions are of the order of 100 F. The composite wall ($\frac{1}{4}$-in. ceramic inside $\frac{1}{16}$-in. metal) reduces metal temperatures by an average of 400 F from the standard case and results in a considerable extension of the thermally safe flight range, down to sea level at Mach numbers up to 2, 54,000 ft at Mach 3 and 80,000 ft at Mach 4.

Larger thicknesses of ceramic coating (assuming that bonding is still feasible) may push the barrier back further. A line for $\frac{1}{2}$-in. ceramic coating was drawn on Fig. 7 to illustrate a potential further depression of the limit line by 10,000 ft. Since the ceramic density is roughly $\frac{1}{3}$ that of metal, the weight increase may be tolerable compared to that incurred in other more complex cooling arrangements. Cooling effectiveness and weight must be considered together when deciding on the optimum tailpipe configuration.

Based on the results of Figs. 6 and 7, it may be stated that for steady state operation single-walled ramjet tailpipes have a well-defined thermal barrier which is dependent on ramjet inlet and exit geometry, gas temperature, and tailpipe shape, thickness and material. Even with the high thrust ramjet used as an example here, suitable wall design may allow adequate protection against thermal failure. Only when high thermal severity interferes with the required flight range, may it be necessary to abandon the simple single-walled design in favor of more complex cooling means. Such means are discussed in a later section.

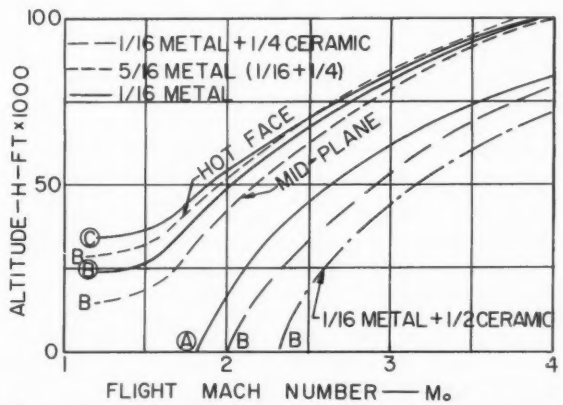

Fig. 7 **Steady state comparison of tailpipes and walls at metal temperature limit 2250 F. 4000 Fg as temperature—maximum power. Wall temperatures are lower at reduced power cruise**

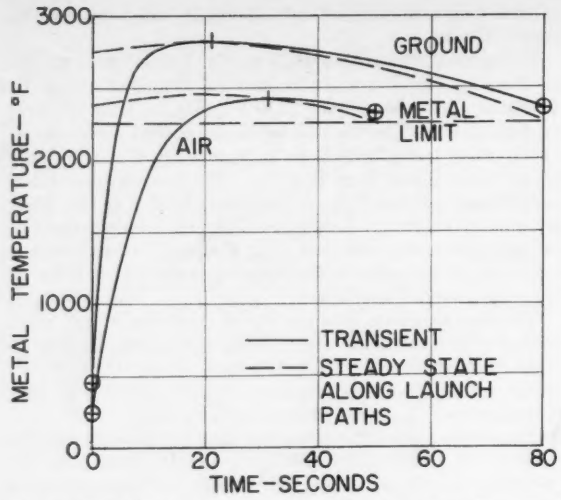

Fig. 8 Transient wall temperatures during air and ground launch—tailpipe B, $\frac{1}{16}$-in. metal wall

Transient Results

For both ground and air launches under ramjet power it was assumed that at time zero the tailpipe wall temperature was equal to the T_{to} value at the end of boost. This assumption is conservative since the wall, exposed both internally and externally to the variable T_{to} during the boost phase, would lag and not generally reach the boost terminal T_{to} (neglecting recovery factors and radiation) when the ramjet was ignited at time zero. For the ground launch (Mach 2 at 4000 ft) this temperature was 448 F and for the air launch (Mach 2 at 40,000 ft) 242 F. All things considered, the ground launch imposes greater thermal severity on the tailpipe because of the higher initial temperature and longer flight through the low altitude region.

Fig. 8 shows tailpipe temperature-time curves for both launch paths for the case of the thermally critical plane of tailpipe B with the thin $\frac{1}{16}$-in. metal wall. The heating rates are quite high initially, averaging about 200 F per sec over the first 10 sec, but are reduced as altitude is gained, despite the continual rise in Mach number. The temperatures reach maxima and then approach the steady state value at the cruise point (Mach 4 at 100,000 ft). The ground launch maximum is reached first (2815 F after 21 sec) despite the longer (80 sec) duration of the complete transient. The air launch maximizes at 2410 F after 31 sec out of 50. Although the cruise point steady state temperature is just at the metal limit, the latter is exceeded over the major portion of both transients.

For comparison purposes the steady state temperatures at conditions along the launch paths are shown by dashed lines. These would only apply if the wall were close to zero thickness so as to reach instantaneous thermal equilibrium at each point. It will be noted that transient and steady state temperatures are equal at the points of maximum transient temperature. This is a consequence of the zero slope of the transient curves at their maxima which knocks out the time-dependent term from the calculation, reducing it to steady state form. Further, the maximum steady state temperature along the path cannot be exceeded during the actual transient. This allows a quick estimate of the maximum possible temperature to be made if the transient is drawn on a plot like Fig. 6.

For a transient comparison of all three tailpipes with the thin wall, Fig. 9 was drawn, using the air launch path. The relative cooling effectiveness of the three tailpipes remains unchanged from the steady state case (Fig. 7), but at any time during the transient the differences A-B and B-C are increased over the corresponding steady state values. This is especially so for the A-B comparison where the maximum transient temperature difference (after 12 sec) is three times the steady state difference at the corresponding M_0-H condition. This shows that a given change manifests itself more strongly during transient than steady state conditions. For the air launch it is seen that temperatures of tailpipe A lie entirely below the metal limit.

The question of how to prevent overheating during launches must be answered before any flying at the cruise point can be done. One of the possibilities is to change the launch paths so that they traverse less dangerous territory. Referring to Figs. 4 and 6, it would appear desirable to increase altitude faster than speed, reaching 100,000 ft at a Mach number less than 4 and then accelerating to Mach 4 in level flight. Alternately, increasing the wall thickness should help a great deal in the transient case because of the increased heat capacity.

Fig. 10 shows the worst case considered, namely, ground launch with tailpipe C. The thin wall reaches 2950 F after 17 sec, and the addition of $\frac{1}{4}$-in. metal only reduces the maximum (at the mid-plane) to 2735 F after 47 sec. However, with the $\frac{1}{4}$-in. ceramic coating the metal never reaches a maximum during the transient. When the cruise point is reached, the metal temperature is 2100 F and still rising. However, it would not be expected to rise any more than another 30 F at the most before dropping to the steady state cruise value. A thinner ceramic coating would thus still have kept the metal below the 2250 F limit. When the maximum temperatures are compared, the differences due to adding material thickness are about double those found in comparable steady state cases (Fig. 7).

It appears possible, therefore, to keep the metal in single-walled tailpipes below structurally limiting temperatures during transients by the use of internal ceramic coatings, provided that no undue amount of low altitude and/or high Mach flight is involved. The air launches analyzed here would fall into this category. Only when inordinately thick and heavy layers of coating are needed to overcome a transient thermal barrier, must recourse be had to more complex

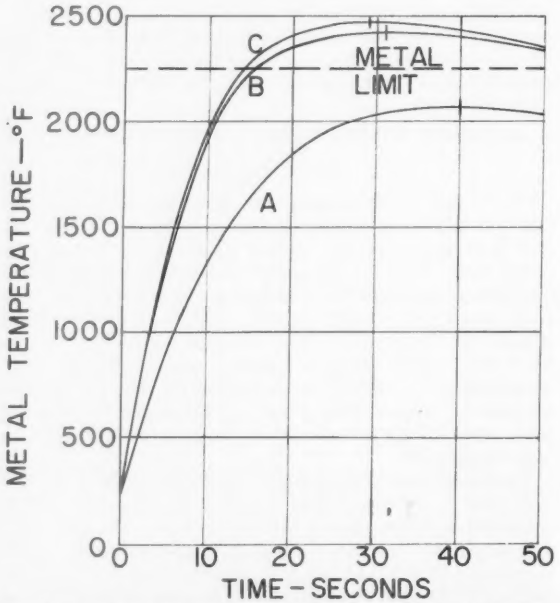

Fig. 9 Transient comparison of tailpipe geometry—air launch, $\frac{1}{16}$-in. metal wall

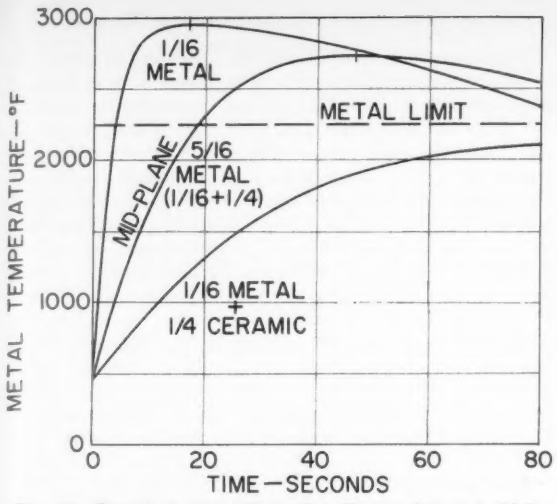

Fig. 10 Transient comparison of wall materials and thicknesses—ground launch, tailpipe C

cooling. Of course, development of coatings with properties superior to those assumed here will make inroads on the barrier.

Although not analyzed here, other in-flight maneuvers and dive trajectories are equally susceptible to the heat transfer approach outlined. If these involve much operation at large angles of attack, the resulting changes in the external and internal flow regimes may lead to tailpipe temperature nonuniformities to which heat transfer methods need to be adapted. Generally, the larger the accelerations, the greater the temperature lags, and the more effective the coatings. Conversely, when accelerations are small, the lags are reduced and the transient temperatures approach the steady state values at the points along the trajectory.

Turbojet-Afterburner Application

Since gas temperatures in turbojet-afterburners are of the same magnitude as in ramjets, single-walled afterburner tailpipes would reach the same temperatures as ramjet tailpipes over the supersonic flight range with comparable gas flows. In actual practice afterburner tailpipes could not always be exposed to the free stream, resulting in increased thermal severity for submerged installation. Further, most supersonic applications require the afterburner on for long periods of time, equivalent to steady state operation. For this, ceramic coatings might be inadequate. The mechanical complication of any variable area exit nozzle arrangement would place additional restrictions on the use of coatings. More complex cooling arrangements (e.g., using compressor bleed air, or external air in ejector-type nozzles) would thus appear more necessary for turbojet-afterburners than for ramjets.

Engine Size Effects

Some remarks might be in order regarding the effect of engine size (in terms of tailpipe diameter). If geometrically similar engines are considered, the gas flow per unit area is constant, so that h_{cg} varies inversely with $(\text{diameter})^{0.2}$ (see Appendix, B), tending toward slightly lower h_{cg} as engine size is increased, i.e., also lower wall temperature. On the other hand, the radiant heat transfer coefficient from hot gas to inner wall (h_{rg}) increases as the diameter increases, counteracting the convection effect.

At low altitudes and high speeds where h_{rg} and h_{cg} are equal (e.g., very nearly so at sea level Mach 4), the radiation effect predominates, resulting in a 30 per cent increase in the total coefficient ($h_{cg} + h_{rg}$) when the present 30-in. size is doubled, and a 16 per cent decrease when it is halved. At high altitudes where h_{rg} is very small compared to h_{cg}, the effect is purely that due to convection, i.e., a 13 per cent decrease in the total coefficient when the size is doubled and a 16 per cent increase when it is halved. Corresponding changes in wall temperature would occur, since the external coefficients are not unduly affected by changes in size.

At intermediate conditions the effects will lie between those quoted; in general there will be a range of flight conditions for which no sensible size effect will be felt. In most cases where only small changes in size are considered, the effects will be small. For steady state lines covering a large flight range, the whole gamut of size effects will be traversed, but for launch paths involving large differences in speed and altitude the size effects might well cancel out.

Thermal Design Factors for Single-Walled Tailpipes

In the foregoing analysis a limited number of variables were investigated and many simplifying assumptions were made, with the prime objective of demonstrating general effects. For a particular engine-vehicle combination many more factors require close examination for adequate thermal tailpipe design or analysis. Table 1 contains a list of such factors, only a few of which were explored numerically. The factors are divided into three categories—internal, wall and external. A short discussion of each follows.

Internal

Air flow variation: Tailpipe temperatures are strongly affected by the amount of ramjet inlet air flow. Fixed geometry designs for operation over a limited Mach number range generally take in less air and give rise to lower thermal severity than the variable geometry used in the paper ramjet for a wide Mach number range.

Fuel combustion characteristics: When chemical fuels capable of higher combustion temperatures than hydrocarbons are burned at maximum heat release, the thermal severity will rise. For analysis, the gas-to-surface radiation properties which depend on the combustion gas constituents must be re-evaluated.

Flow and temperature nonuniformities: Depending on the characteristics of ramjet diffuser and burner systems, nonuniformities may be introduced, resulting in flow and temperature stratification inside the tailpipe. The gas-to-surface convection at a given point, being primarily a function of gas boundary layer velocity and temperature, must be adjusted to the local boundary layer conditions, which may include chemical reaction. Likewise, gas-to-surface radiation will be influenced by gas temperature nonuniformities.

Gas pressure oscillations: Both aerodynamic and combustion pressure oscillations may make themselves felt in the tailpipe gas. Heat transfer rates generally tend to increase with amplitude, but not enough is known about such effects at the present time.

Exit throat sizes: The smaller the throat area, the more acute the heating at the throat and the poorer the external convective cooling (e.g., tailpipe C). For very small exits it may be found necessary to use additional cooling at the throat.

Axial heat transfer effects: In practice all the heat transfer is not purely lateral. One axial effect is radiation from the interior surface of the divergent part of the tailpipe exit directly to the environs, resulting in improved cooling for some distance forward of the nozzle exit plane. Another is the internal boundary layer history upstream of the thermally critical plane.

Wall

Surface emissivities: For the inner surface a low emissivity is desirable to reduce the gas-to-wall heat flow, whereas for the outer surface the opposite is true, to dissipate as much heat as possible. For this reason ceramics of low emissivity are useful internally and oxidized surfaces help externally. Generally, it is always economical to treat surfaces for a desirable emissivity characteristic because of the large gains possible.

Surface irregularities: For low heating and good cooling, it is desirable to keep the inner surface smooth (tending toward minimum effective heat transfer surface and a low transmittance laminar boundary layer) and the outer surface rough (for maximum area and highly turbulent high transmittance boundary layer). Surface finish should therefore be closely controlled.

Material properties: For transient use, low thermal diffusivity (i.e., low thermal conductivity, high density and high specific heat) is desirable if elevated hot face temperatures can be tolerated (e.g., for a ceramic). If not (e.g., for metal), high density and specific heat alone are desirable. For steady state, only thermal conductivity is important, a high value being desirable for low hot face temperatures, and vice versa. High contact resistance across a metal-ceramic bond will assist cooling, since the ceramic can stand up under the resultant high hot face temperature. More information on any such contact resistance is needed.

Wall thickness: As thickness is increased, the inside surface temperature rises and the outside surface temperature drops. Also, the total heat flow across the wall is reduced. Thus thick ceramic walls may be used, but metal walls should be kept thin.

Wall vibration: This is unavoidable in practice and affects heat transfer rates in a manner not well understood as yet.

Axial heat transfer effects: When internal nonuniformities such as axial and circumferential gas temperature variation are present, three-dimensional conduction takes place in the wall. This leads to similar nonuniformities in wall temperature which are structurally undesirable.

External

Air flow nonuniformities: The boundary layer significant for external convection may be influenced by flow nonuniformities arising from interaction of ramjet and vehicle shapes and surfaces. These include the ramjet supporting strut to fuselage or wing tip, aerodynamic interference from surfaces of vehicle or a second ramjet (shock wave-boundary layer interaction), and the forward contour of the ramjet itself.

Radiation nonuniformities: The outer surface actually radiates to a number of objects at different sink temperatures with different shape factors, rather than to a uniform environment. The receivers include sky, ground and surfaces of vehicle and ramjet(s), the individual contributions being affected by position relative to ground and sun.

Maneuvers: Changes in angle of attack, acceleration, roll, pitch, etc., will change flow patterns both inside and outside the ramjet, and affect the whole heat transfer system. In some cases one-sided heating may result, which must be designed for if the severity of the maneuver is foreseeable.

Flight range: This is the major thermal design factor for steady state flight, as shown in the graphs.

Transient trajectories: These constitute the major thermal design factor for transient flight, e.g., during launch, as shown in the graphs. Often it is possible to make changes in transients rather than in the physical parts of the ramjet to avoid thermal failures.

Axial heat transfer effects: Important here is the history of of the external boundary layer upstream of the thermally critical plane.

More Complex Tailpipe Cooling Designs

The results of the analysis indicated the need in a number of cases for cooling additional to that provided by the single-walled design. This need was more prevalent for steady state than transient operation since thicker and thermally more insulating materials were more effective in the latter than in the former case. In such an event it must first be determined what length and part of the tailpipe is in need of additional cooling. Perhaps only the area in the immediate vicinity of the exit nozzle throat is thermally critical; on the other hand, the entire length may need protection. Needless to say, the introduction of cooling devices must compromise the flight performance to some degree; it may be felt as a penalty in gross thrust, weight, drag, complexity, cost, etc.

It is only intended here to remark briefly on some of the devices or systems which could be used for cooling tailpipes of externally mounted supersonic ramjets. Three categories may be mentioned in ascending order of effectiveness: (a) Structural changes not affecting the internal flow, (b) use of air as a coolant, and (c) use of other fluids as coolants.

Under (a) may be mentioned increases of the effective outer surface heat transfer area by radial fins or corrugations. These may be added over the tailpipe areas in need of additional heat dissipation, such as the nozzle throat. For large contraction ratio nozzles, external scoops directing freestream air parallel to the convergent part of the nozzle might be useful in increasing the convective heat transfer at the throat. Such devices may appear indicated in marginal situations where a complete redesign is not possible or desired. Additional weight and drag are the principal disadvantages.

Systems involving (b) may either scoop air from the free stream or bleed it off the ramjet diffuser. In either case a second cylindrical wall inside or outside the nominal tailpipe is introduced, forming an annular parallel-flow cooling passage. Since the divergent part of the nozzle is rarely in need of extra cooling, the passage generally terminates at the nozzle throat. If internal, the second wall may be shortened to take advantage of the film or boundary layer cooling effected over a short axial distance by the air spilling from the passage at lower temperature than that of the combustion gas with which it mixes. In these systems the lowest air temperature available for cooling is the flight total temperature T_{to} (for turbojet-afterburners with compressor bleed an even higher temperature) which limits the effectiveness at high Mach numbers and low altitudes. A weight penalty is unavoidable, but when using external air it may be possible to keep drag losses to a minimum (or even increase the net thrust) by a suitable ejector-exit nozzle design.

Designs in category (c) have the widest latitude. First, liquids (which have better cooling properties than gases like air) may be used; second, provision may be made for sink temperatures below T_{to}; and third, the more efficient counterflow heat exchange principle may be used. The system may be open or closed. An example of the former might be the use of the liquid ramjet fuel itself, introduced as a counterflow coolant at the tailpipe exit and flowing forward in annular passage, finally entering the ramjet fuel injection system in the diffuser. This type of system is the bulkiest of all, and, if closed, requires additional apparatus in the vehicle. On the other hand, when tailpipe thermal severity is extreme, it is the only one which holds out hope of providing adequate cooling.

It may be possible to optimize tailpipe cooling by a combination of systems, e.g., a refrigeration system in category (c) may be used to cool air for direct use in a system of category (b). As ramjets proceed to higher and higher flight Mach numbers, the thermal barrier will become more restrictive, and more effective tailpipe cooling will be needed to combat it.

Conclusion

Single-walled thin metal tailpipes used on externally mounted supersonic ramjets encounter a thermal barrier only in regions of high Mach number and low altitude. The barrier may be pushed back by use of internal ceramic coatings whose effectiveness is more marked during transient than steady state operation. Ultimately, the thermal limits of ramjet flight can be extended only by more complex means of tailpipe cooling.

Acknowledgments

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Table 1 Some thermal design factors for single-walled tailpipes

Internal	Wall	External
Air flow variation	Surface emissivities	Air flow nonuniformities
Fuel combustion characteristics	Surface irregularities	Radiation nonuniformities
Flow and temperature nonuniformities	Material properties	Maneuvers
Gas pressure oscillations	Wall thickness	Flight range
Exit throat size	Wall vibration	Transient trajectories
Axial heat transfer effects	Axial heat transfer effects	Axial heat transfer effects

APPENDIX

Heat Transfer Analysis

A. Assumptions

1. *Internal gas:* Hot, fully turbulent gas, consisting of stoichiometric products of hydrocarbon-air combustion, flows at known weight rate W_g through tailpipe, having a uniform and constant total temperature T_{tg} at the thermally critical plane (diameter D).

2. *Gas to inner wall surface:* Heat transfer by radiation and forced convection. Radiation temperature difference is static gas temperature at diameter D, T_g, minus tailpipe inner surface temperature T_h, with coefficient h_{rg}. Inner surface emissivity e_h is 0.6 for metal, or 0.3 for ceramic. Convection temperature difference is T_{tg} minus T_h, with coefficient h_{cg}.

3. *Inner to outer wall surface:* Heat transfer by radial conduction neglecting contact resistance across metal-ceramic bond and temperature gradient across thin ($^1/_{16}$ in.) metal wall.

4. *Outer wall surface to outside environs:* Heat transfer by radiation and forced convection. Radiation temperature difference is tailpipe outer surface temperature T_{mc} minus flight ambient static temperature T_o, with coefficient h_{ro}. Outer surface emissivity e_o is 0.8 for oxide-coated metal. Convection temperature difference is T_{mc} minus flight total temperature T_{to}, with coefficient h_{co}.

5. *External air:* Fully turbulent flow along the tailpipe surface at free stream Mach number M_o, with an equivalent flat plate length of 10 ft at the thermally critical plane. The h_{co} so found is halved for tailpipe C (see Fig. 5), but retains full value for tailpipes A and B. The angle of attack is taken as close to zero.

6. *Conservative nature of assumptions:* The gas and outside temperatures assumed resulted in increased over-all thermal severity compared to actual conditions. For convection the recovery factors were neglected, i.e., T_{tg} and T_{to} were used instead of adiabatic wall temperatures. For outside radiation T_o was used as sink temperature rather than a lower value such as absolute zero.

B. Heat Transfer Coefficients for Radiation and Convection

h_{rg}: Evaluated by methods of (5, p. 82 et seq.), considering H_2O and CO_2 radiation to gray walls, as a function of e_h, T_g, D, P_g and T_h; P_g is found from continuity equation and known W_g, T_{tg}, D and M_g; T_h requires iteration for steady state and is known from previous step for transient.

h_{cg}: Evaluated from turbulent heat transfer equations given in (5, p. 219), or their equivalents, as follows:

$$h_{cg} = (\text{const})(W_g)^{0.8}(T_h + T_{tg})^{0.152}/(D)^{1.8}$$
$$= (\text{const})(G_g)^{0.8}(T_h + T_{tg})^{0.152}/(D)^{0.2}$$

T_h requires iteration for steady state; is known from previous step for transient.

h_{ro}: Evaluated from $h_{ro} = (e_o) \cdot (\text{Stefan const}) \cdot (T_{mc}^2 + T_o^2) \cdot (T_{mc} + T_o)$; T_{mc} requires iteration for steady state and is known from previous step for transient.

h_{co}: Evaluated from results of (6) with flat plate length of 10 ft as function of M_o and H.

C. Steady State Methods

Heat flow balance for metal wall internally coated with ceramic at T. C. P., neglecting surface curvature because of small x/D:

$$Q = h_{rg}(T_g - T_{ah}) + h_{cg}(T_{tg} - T_{ah}) =$$
$$(k_a/x_a)(T_{ah} - T_{mh}) = (k_m/x_m)(T_{mh} - T_{mc})$$
$$= h_{ro}(T_{mc} - T_o) + h_{co}(T_{mc} - T_{to})$$

For this most general case there results

$$T_{mh} = \frac{(h_{rg}T_g + h_{cg}T_{tg}) + X(h_{ro}T_o + h_{co}T_{to})}{(h_{rg} + h_{cg}) + X(h_{ro} + h_{co})}$$

where

$$X = \frac{1 + (x_a/k_a)(h_{rg} + h_{cg})}{1 + (x_m/k_m)(h_{ro} + h_{co})}$$

When temperature gradient in thin metal wall is neglected, this reduces to $X = 1 + (x_a/k_a)(h_{rg} + h_{cg})$; and when in addition no ceramic coating is present, $X = 1$.

For thick metal wall with temperature gradient but without ceramic coating, the formula reduces to $(1/X) = 1 + (x_m/k_m)(h_{ro} + h_{co})$.

Once T_{mh} is found, the last two equations of the balance may be solved for T_{mc}, yielding

$$T_{mc} = \frac{(k_m/x_m)T_{mh} + (h_{ro}T_o + h_{co}T_{to})}{(k_m/x_m) + (h_{ro} + h_{co})}$$

Finally

$$T_{mm} = (T_{mc} + T_{mh})/2$$

In practice, since h_{rg} and h_{cg} are functions of T_{ah}, and h_{ro} depends on T_{mc}, an iterative numerical method was employed to solve for the metal temperatures, utilizing digital computing machines. Dependence of h_{co} on T_{mc} in a more refined method may also be treated thus.

D. Transient Methods

1. For the metal wall without temperature gradient and

(*Continued on page 541*)

Upper Bounds and Conservative Estimates for Aerodynamic Heating at Great Altitudes

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A simple procedure is developed for obtaining upper bounds for aerodynamic heating at high speeds and altitudes. The procedure is based on energy considerations, and assumes the most unfavorable flow conditions. In nonmarginal cases, such as the launching vehicle for an artificial satellite, these upper bounds result in skin temperatures low enough to serve as a guide for practial design purposes.

Introduction

ATTAINING a reliable prediction of skin temperatures of high speed, high altitude vehicles involves numerous difficulties, for several reasons. The elementary theory of convective heat transfer breaks down under the conditions of high speed flight in rarefied air. The familiar concepts of discontinuous shock waves and thin boundary layers can no longer be used when the mean free path of the air molecules becomes comparable to the continuum flow boundary layer thickness. Moreover, the conversion of a great part of the kinetic energy of the flow into random kinetic energy of the molecules often leads to temperatures which are sufficient to dissociate the air molecules into neutral atoms or ions and free electrons.

There is some information available on the equilibrium state of the air at very high temperatures. For the flight conditions considered here, however, these data are not always applicable, since the relaxation time may be of the same order of magnitude as the time that it takes the free flow to travel the length of the body.

It is relatively simple, however, to obtain some upper bounds for aerodynamic heating. In order to be useful for practical design purposes, these bounds should result in skin temperatures lower than those which available and otherwise suitable materials can withstand.

An example of the foregoing might be a rocket launched from the ground into a flight path outside the atmosphere, i.e., the launching vehicle for an artificial satellite. In the lower atmosphere where density is high, the velocity of such a vehicle would be relatively low and the aerodynamic heating, therefore, would be moderate. At extreme altitudes, the heating becomes negligible, since the density is so low that only a small amount of energy is available for transfer to the skin. On the other hand, in the case of re-entry, the procedure described in this paper might be valuable to show that a certain vehicle with low re-entry velocity would not burn up.

Upper Bounds for the Temperature of Sharp Leading Edges or Pointed Noses

The most severe aerodynamic heating occurs at those points which are directly exposed to the flow, such as the nose and the leading edges of fins. The heating is especially severe for pointed ends, because of their small heat capacity and their poor ability to conduct heat.

In the following, the heat capacity of the body as well as the heat conduction in the skin and from the skin into the interior of the body will be disregarded. This will certainly lead to an overestimation of the transient temperature while it is rising. On the other hand, the temperature after passing through the maximum might be underestimated if the "thermal inertia" of the body is too great. At any rate, the maximum of the temperature will be conservatively estimated.

In order to estimate the maximum possible temperature at any point of a body we may first note that the *temperature in the flow* can nowhere exceed the stagnation temperature. In fact, the stagnation temperature

$$T_0 = T_\infty \left(1 + \frac{\gamma - 1}{2} M^2\right) \quad [1]$$

(where T_∞ is the ambient temperature, $\gamma = c_p/c_v$, and M is the Mach number) is that temperature which the gas would assume if all its kinetic energy were converted into heat without exciting any internal degrees of freedom of the molecules, without energy consumption by dissociation, ionization or radiation, and without heat conduction from the hotter parts of the flow field to cooler parts.

The only possibility of exceeding T_0 somewhere in the flow field would be by the liberation of latent chemical energy, e.g., by the compression of a cool hydrogen-oxygen mixture in a strong shock wave. However, all possible chemical changes in air (such as $O_2 \rightarrow O + O$ or $O_2 + N_2 \rightarrow 2NO$) require energy and, hence, lower the temperature. We obtain thus the first estimate for a body[2] in the flow

$$T_w \leq T_\infty(h) \cdot \left(1 + \frac{\gamma - 1}{2} M^2\right) \quad [2]$$

where $T_\infty(h)$ is a function of the altitude, the value of which can be taken from tables of the standard atmosphere. (We might also consider γ as a function of h, due to the variation of the composition of the atmosphere at great altitudes, e.g., formation of ozone or atomic oxygen. This effect has been disregarded, but could easily be taken into account.)

Equation [2] is only useful for moderate Mach numbers because of the rapid increase of T_0 with M. We proceed, therefore, to derive a second upper bound for higher speeds. This

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[2] This is correct only in continuum flow, since it implies that the greatest part of the available energy is retained in the gas and only a small portion is transferred to the body. In a free molecule flow, it is obvious that any part of the kinetic energy can be transferred to the body upon the impact of the molecules on the surface. Hence Equation [2] will only be used for comparatively low altitudes and will be replaced by the subsequently derived inequality [7] at greater altitudes. For experimental evidence of "temperature recovery factors" above 1 at extremely low pressures, cfr. S. A. Schaaf, JET PROPULSION, vol. 26, April 1956, p. 247, and R. M. Drake and G. H. Backer, *Trans. ASME*, vol. 74, 1952, p. 1241.

second bound is obtained from the observation that the total heat energy absorbed by the body cannot be more than the relative kinetic energy contained in the volume of air through which the body has passed. Assuming that these two amounts of energy are equal would imply that all this air comes to rest relative to the body and travels along with it. It also implies that the air is cooled down to the ambient temperature T_∞ by a heat sink inside the body of such a strength that it keeps the temperature of the body at T_∞. This is obviously a fantastic assumption, but we are going even one step further. We suppose that all of the available energy is used for heating the body to such a temperature T_{rad}, at which it would radiate away all the energy which it receives. This fictitious temperature, then, is an upper bound for the skin temperature of the body.

We are now interested in the nose region which in practice is not a mathematical point, but a small rounding normal to the flow. Hence we apply our procedure to a flat plate of unit area normal to the flow. The available kinetic energy in this case is

$$E_1 = \frac{\rho(h)}{2} U^2 \cdot U = \frac{1}{2} \rho(h) a(h)^3 M^3 \frac{\text{ft·lb}}{\text{sec·ft}^2} \quad [3]$$

where $\rho(h)$ and $a(h)$ are the density and the velocity of sound at the altitude h. On the other hand, this area radiates away energy at the rate of

$$E_2 = \epsilon \sigma T_w^4 \frac{\text{ft·lb}}{\text{sec·ft}^2} \quad [4]$$

where $\epsilon \leq 1$ is its emissivity, σ the radiation constant

$$\sigma = 3.8 \times 10^{-10} \frac{\text{ft·lb}}{\text{ft}^2 \text{ sec } ^\circ\text{R}^4} \quad [5]$$

and T_w is its surface temperature in degrees Rankine. We can assume $\epsilon \approx 1$, since we can coat the nose with some dark and sufficiently heat resisting material, and thus obtain

$$E_2 = 380 \left(\frac{T_w}{1000}\right)^4 \frac{\text{ft·lb}}{\text{ft}^2\text{·sec}} \quad [6]$$

Combining Equations [3 and 6], the equilibrium temperature becomes

$$T_w = 190 \sqrt[4]{\rho(h) a(h)^3} \cdot M^{3/4} \quad [7]$$

Thus, for a given altitude, the equilibrium temperature of the nose cannot exceed a value which is proportional to the $^3/_4$ power of the Mach number. Combining this result with Equation [2], and assuming the value $\gamma = 1.4$, we obtain

$$T_w < T_M = \text{Min} \left\{ T_\infty(h)[1 + (M^2/5)];\ 190 \sqrt[4]{\rho a^3} M^{3/4} \right\} \quad [8]$$

This equation holds true only for the equilibrium temperature at the altitude h. However, when a rocket travels from the ground to very high altitudes, its temperature at the altitude h will always be between its actual temperature at the altitude $h - \delta$ and the equilibrium temperature corresponding to the altitude h. Hence, the maximum temperature which it will experience cannot be greater than the maximum of T_M with respect to h.

The problem, then, is to evaluate the very rough estimate of Equation [8]. Fig. 1 gives several curves for T_M as a function of M for various altitudes. The atmospheric data were taken from (1).[3] It can be seen that the expression $T_\infty(h) \cdot [1 + (M^2/5)]$ gives the lower estimate at low altitudes for all possible Mach numbers, whereas the expression $190 \sqrt[4]{\rho a^3} \cdot M^{3/4}$ yields the lower estimate at high altitudes. Fig. 1 shows that the aerodynamic heating cannot even maintain the ambient temperature at $h = 350{,}000$ ft unless the Mach number exceeds approximately 2.5.

[3] Numbers in parentheses indicate References at end of paper.

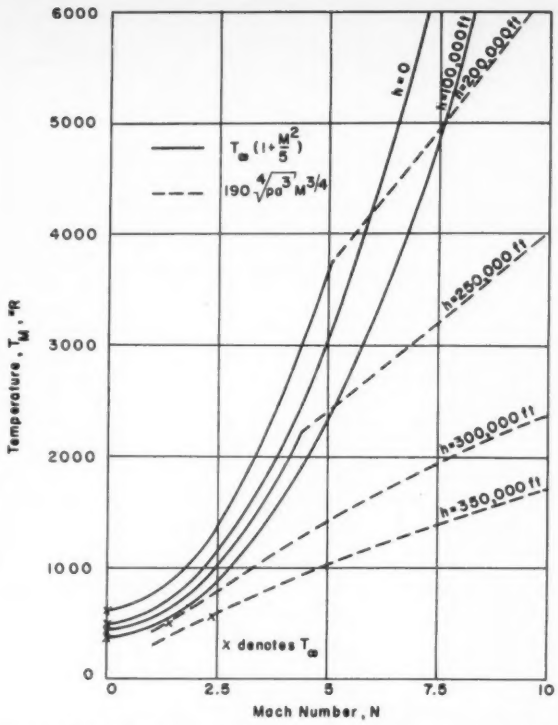

Fig. 1 Upper bound for equilibrium temperature at great altitudes (see Equation [8])

This indicates to us immediately the altitudes above which aerodynamic heating is certainly no longer a problem.

In Fig. 2, Equation [8] is applied to a trajectory which might be typical for the launching of an artificial satellite. It can be seen that the temperature of the nose remains below approximately 3200 R. This is certainly high, but still somewhat below the melting point of platinum ($\backsimeq$3600 R) and even further below that of some other metals, oxides and ceramic materials. Hence, we may conclude that materials are available which can stand the intense aerodynamic heating at the nose and at leading edges. Our cautious approach, in fact, will probably exclude a number of cheap and easily handled materials.

We may also conclude that the peak temperature for this case will be obtained in the neighborhood of $h = 200{,}000$ ft. At altitudes of 200,000–250,000 ft the mean free path of the air molecules is of the order of 0.01–0.1 in., i.e., no longer negligible in comparison with the boundary layer thickness near the nose. Hence, a more elaborate calculation of the peak temperature would be impossible without considering slip flow effects. On the other hand, the mean free path is not yet large enough to have the conditions of true free molecule flow at some distance from the exposed points of the vehicle. To consider the heating of the skin, we will therefore need information about the skin friction well into the slip-flow region, but not necessarily covering the region of free molecule flow.

Conservative Estimates for the Skin Temperature

Equation [8] generally results in temperatures much too high to serve as guides for the selection of suitable materials for the main parts of the vehicle. It is therefore necessary to use methods which are not quite so ultraconservative to estimate the skin temperatures.

Speaking quite generally, the amount of heat absorbed by a body in a high speed flow is a certain part κ of the work of the friction forces. Neglecting heat conduction in the skin and

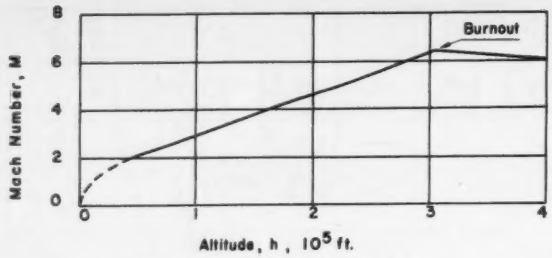

Fig. 2(a) Typical trajectory data

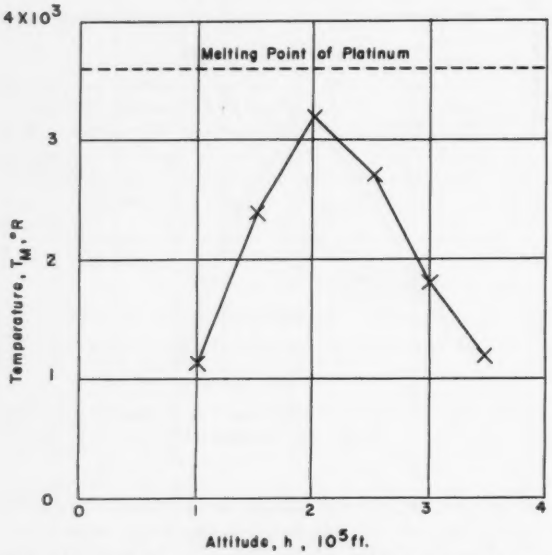

Fig. 2(b) Upper bound for the temperature of the nose for the trajectory in Fig. 2(a)

from the skin into the interior of the body we may write

$$Q = \left(\kappa \cdot c_f \cdot \frac{\rho a^2}{2} M^3 - \epsilon\sigma T_w^4\right) \frac{\text{ft·lb}}{\text{ft}^2\,\text{sec}} \quad [9]$$

where c_f is the friction coefficient for a distance x from the nose. Denoting the specific heat capacity of the skin by G (ft lb/ft² °R)

$$G = \text{specific heat}\left[\frac{\text{Btu}}{\text{slug °R}}\right] \times \text{density}\left[\frac{\text{slug}}{\text{ft}^3}\right] \times \text{heat equivalent}\left(\frac{780\ \text{ft lb}}{\text{Btu}}\right) \times \text{thickness [ft]} \quad [10]$$

we obtain the rate of temperature increase with the time t

$$\frac{dT_w}{dt} = \frac{Q}{G} = \frac{\kappa}{2G}\rho(h)a(h)^3 c_f M^3 - \frac{\epsilon\sigma}{G} T_w^4 \quad [11]$$

This differential equation has to be solved by numerical integration, most conveniently by a stepwise calculation with a finite time interval.

In Equation [11], the values of G (possibly variable with T_w), and $\epsilon\sigma$ can be assumed as known. The Mach number M and the altitude h are known as functions of the time from the trajectory; the density $\rho(h)$ and the sound velocity $a(h)$ are known from tables of the standard atmosphere. It remains thus to introduce suitable assumptions for κ and c_f. κ cannot exceed 1. Moreover, it can be generally shown for continuum flow that $\kappa = 1/2$ if the Prandtl number is unity and if the skin is kept at the ambient temperature T_∞. If the skin is heated above T_∞, κ decreases and becomes zero at the adiabatic wall temperature T_{aw}. Experimental values of κ are quoted to be between 15 and 55 per cent (2, p. 21). Since the skin is actually heated to a temperature greater than T_∞, but probably not as high as T_{aw} in a high speed flow of rarefied air, the assumption $\kappa = 1/2$ (independent of T_w) appears to be reasonably safe.

A decision about the friction coefficient c_f is much more difficult to make. In a supersonic continuum flow past a cone, the static pressure is constant along the surface, provided that the Mach number is high enough for the shock wave to be attached. Hence, we can use Mangler's transformation of the boundary layer of a flat plate (3) and obtain for the mean friction coefficient of a cone in laminar flow

$$c_{f\,\text{lam}} = \frac{1.53}{\sqrt{Re}} \quad [12]$$

where

$$Re = \frac{u_1 x \rho_{BL}}{\mu_{BL}} \quad [13]$$

is the Reynolds number at the distance x from the vertex of the cone. The velocity u_1 exists just outside the boundary layer. The density ρ_{BL} and the viscosity μ_{BL} are average values, evaluated at a reference temperature inside the boundary layer.

Equation [12] is unsuitable for $Re \to 0$, since it results then in $c_f \to \infty$. However, H. Mirels (4) has given an approximate formula for $c_{f\,\text{plate}}$ which spans the whole range from laminar continuum flow to free molecule flow. Using Mangler's transformation,[4] Mirels' formula would yield for a cone

$$c_{f\,\text{cone}} = 1.155\, c_{f\,\text{plate}} \approx \frac{1.56}{M} \frac{e^{z^2}[1 - \phi(z)] - 1 + (2z/\pi)}{z^2} \quad [14]$$

with

$$z = 1.145 \frac{\sqrt{Re}}{M}, \quad \phi(z) = \frac{2}{\pi}\int_0^z e^{-t^2}\,dt$$

This formula would be well suited for our purpose, except for the fact that one of the assumptions for its derivation is a constant pressure on the surface of the cone. This is essentially true for continuum flow with an attached shock wave, but it is not quite true under slip flow conditions. The low Reynolds number then causes a strong increase of the boundary layer thickness near the nose so that the pressure distribution of the cone becomes somwhat like that of an ogive in an inviscid flow. We shall neglect this difference so that the subsequent estimate holds for a "body with zero pressure gradient." The shape of such a body will, of course, depend on both the Mach number and the Reynolds number; it will have a slightly concave meridian curve instead of the straight line for a cone.

Due to the certain weakness of the formula for c_f, a further simplification will be justified, especially if it increases the values of c_f. Introducing for the moment the abbreviation

$$g(z) = \frac{e^{z^2}[1 - \phi(z)] - 1 + (2z/\sqrt{\pi})}{z^2} \quad [15]$$

it is easily seen that

$$g^*(z) = \frac{2}{\sqrt{\pi}} \frac{1}{1 + z} \quad [16]$$

is a very good approximation for $g(z)$ (Fig. 3) In fact, Equation [16] yields only 13 per cent more than Equation [15] for

[4] The applicability of this transformation is somewhat questionable under the present conditions, especially for conditions close to a free molecule flow. However, since the most critical heating occurs in the present case below the region of free molecule flow, Equation [14] appears to be safe enough for our purpose.

$z = 0$ (free molecule flow) and not quite 2 per cent less than Equation [15] for $z = 3$, by substituting g^* for g. Equation [14] may thus be written

$$c_{f\text{cone}} \backsimeq \frac{1.56}{M} \frac{2}{\sqrt{\pi}} \frac{1}{1 + 1.145\,(\sqrt{Re}/M)} < \frac{1.76}{M + \sqrt{Re}} \quad \ldots [17]$$

Hence, substituting

$$c_{f\text{cone}} \backsimeq \frac{1.76}{M + \sqrt{Re}} \quad \ldots [18]$$

we obtain values which are about 14 per cent too high for laminar continuum flow ($M \ll Re$) and about 13 per cent high for free molecular flow ($Re \ll M$) as compared to values from Equation [14]. In the intermediate region, we obtain consistently higher values than from Mirels' formula with the exception of $\sqrt{Re}/M \backsimeq 0.4$, where the two formulas yield practically the same result (Fig. 4).

Accepting Equation [18] as a suitable approximation for the friction coefficient in rarefied air flow and assuming $\kappa = 1/2$, we obtain the differential equation [11] for the skin temperature in the form

$$G \frac{dT_w}{dt} = 0.44\rho(h)a(h)^3 \frac{M_1^2}{1 + (\sqrt{Re}/M_1)} - \epsilon\sigma T_w^4 \quad \ldots [19]$$

In order to solve this equation, we have still to find the Reynolds number (Equation [13]); i.e., we have to make a decision about the viscosity and the density in the boundary layer. For our purpose, it is sufficient to find a lower bound for Re: This will be obtained from a value of ρ_{BL} which is too low and a value of μ_{BL} which is too high.

The average density ρ_{BL} can be determined from the density ρ_1 just outside the boundary layer, since the static pressure in the boundary layer equals approximately the static pressure just outside the boundary layer

$$\rho_{BL} = \rho_1 \frac{T_1}{T_{BL}} \quad \ldots [20]$$

where T_{BL} is the average temperature in the boundary layer. We assume T_1 and ρ_1 as the values of T and ρ on the surface of the cone in an inviscid flow; T_{BL} will be assumed as smaller than the stagnation temperature. Thus

$$\rho_{BL} > \frac{\rho_1}{1 + \frac{\gamma - 1}{2} M_1^2} \quad \ldots [21]$$

This inequality holds for undissociated air with a constant value of γ. Actually γ decreases somewhat with increasing

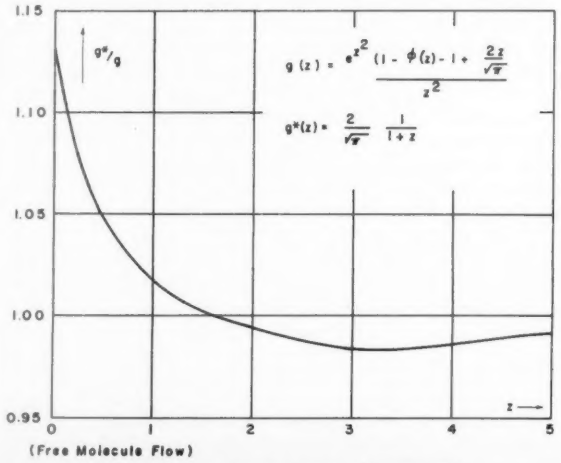

Fig. 3 Comparison between $g(z)$ and $g^*(z)$

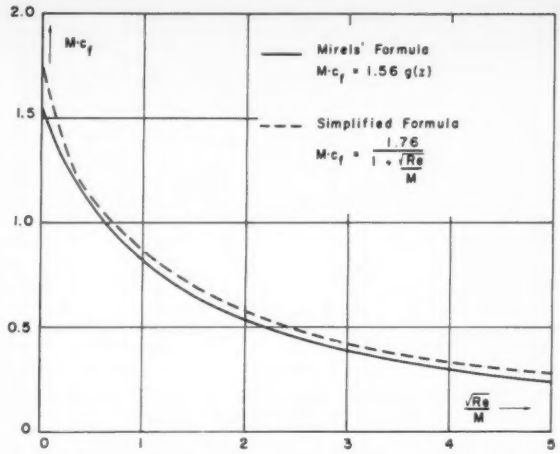

Fig. 4 Comparison between Mirels' formula for the friction coefficient of a body with zero pressure gradient, and the simplified formula $C_f = 1.76/(M + \sqrt{Re})$

temperature due to the gradual excitation of vibrational degrees of freedom of the molecules. Neglecting the decrease of γ obviously strengthens the inequality for ρ_{BL}. Thus

$$\rho_{BL} > \frac{\rho_1}{1 + (M_1^2/5)} \quad \ldots [22]$$

Equation [22] holds for temperatures below about 2700 R. Above 2700 R, the air starts to dissociate. Since the dissociation requires energy, we may assume that the temperature of a partially dissociated boundary layer is not higher than the free-stream stagnation temperature. However, the number of molecules is increased by the dissociation, and hence the density at constant pressure decreases in the same proportion. The limit is obviously the complete dissociation, where the density becomes half the value of Equation [22]. Hence it will be conservative to write

$$\rho_{BL} > \frac{\rho_1}{2[1 + (M_1^2/5)]} \text{ for } 2700^\circ \text{ R} < T_1[1 + (M_1^2/5)] \quad \ldots [23]$$

On a similar basis, we can find conservative estimates for viscosity coefficient μ. For undissociated air (definitely for $T_1[1 + (M_1^2/5)] < 2700$ R) the viscosity is a function of the temperature only.

$$\mu = \frac{2.3 \times 10^{-8} \sqrt{T}}{1 + (200/T)} \frac{\text{lb sec}}{\text{ft}^2} \text{ for } T < 2700^\circ\text{R} \quad \ldots [24]$$

This formula (2, Equation 28) can obviously be simplified to

$$\mu_{BL} < 2.3 \times 10^{-8} \sqrt{T} \frac{\text{lb sec}}{\text{ft}^2} \text{ for } T_{BL} < 2700^\circ\text{R} \quad \ldots [25]$$

An approximate formula (2, Equation 30) for partly dissociated air is

$$\mu = \frac{2.3 \times 10^{-8} \sqrt{T}}{1 + \frac{200}{T}} \left(\frac{1}{1 + 0.89 \frac{C_A}{C_M}} + \frac{\sqrt{2}}{1 + 1.26 \frac{C_M}{C_A}} \right) \frac{\text{lb sec}}{\text{ft}^2} \quad \ldots [26]$$

where C_M and C_A are the concentrations of molecules and atoms, respectively ($C_M + C_A = 1$). Since the expression in the parentheses varies continuously from 1 to $\sqrt{2}$ as C_M varies from 1 to 0 (complete dissociation) we have

$$\mu < 2.3 \times 10^{-8} \sqrt{2T} \frac{\text{lb sec}}{\text{ft}^2} \text{ for } T_{BL} > 2700^\circ\text{R} \quad \ldots [27]$$

These inequalities are strengthened if T is replaced by a

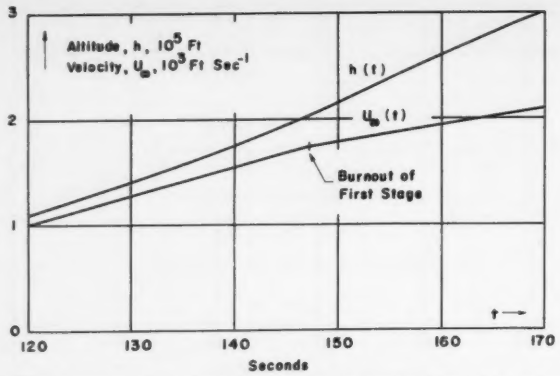

Fig. 5 Typical trajectory data for an estimate of the skin temperature in the slip-flow region

value which is too large. We may thus write

$$\mu_{BL} < 2.3 \times 10^{-8} \left\{ \frac{\sqrt{T_1 \left(1 + \frac{M_1^2}{5}\right)}}{\sqrt{2T_1 \left(1 + \frac{M_1^2}{5}\right)}} \right\} \frac{\text{lb sec}}{\text{ft}^2} \quad \ldots [28]$$

for

$$T_1 \left(1 + \frac{M_1^2}{5}\right) \begin{matrix} < 2700^\circ \text{ R} \\ > 2700^\circ \text{ R} \end{matrix}$$

A slight modification of Equation [28] is convenient. The fact that μ_{BL} is approximately proportional to $\sqrt{T_1}$ suggests the introduction of the velocity of sound a_1, which is also proportional to $\sqrt{T_1}$. Assuming constant composition of the air and constant $\gamma = 1.4$, we have

$$a_1 = 49 \sqrt{T_1} \frac{\text{ft}}{\text{sec}} \quad \ldots [29]$$

This yields

$$\mu_{BL} < \frac{4.7}{5.7} \times 10^{-10} a_1 \sqrt{1 + \frac{M_1^2}{5}} \frac{\text{lb sec}}{\text{ft}^2} \quad \ldots [30]$$

for

$$T_1 \left(1 + \frac{M_1^2}{5}\right) \begin{matrix} < 2700^\circ\text{R} \\ > 2700^\circ\text{R} \end{matrix}$$

Introducing [22, 23, 30] into [13], we obtain the estimate of the Reynolds number

$$Re = \frac{u_1 \rho_{BL} x}{\mu_{BL}} > 2.1 \times 10^9 \rho_1 x \frac{M_1}{\left(1 + \frac{M_1^2}{5}\right)^{5/2}} \quad \ldots [31]$$

for

$$T_1 \left(1 + \frac{M_1^2}{5}\right) < 2700^\circ\text{R}$$

and

$$Re > 7.4 \times 10^8 \rho_1 x \frac{M_1}{\left(1 + \frac{M_1^2}{5}\right)^{5/2}} \quad \ldots [31a]$$

for

$$T_1 \left(1 + \frac{M_1^2}{5}\right) > 2700^\circ\text{R}$$

With these values of Re, the differential equation [19] can be integrated and the result of the integration is likely to be a conservative estimate of the transient skin temperature, at least as long as it is rising.

As a numerical example, let us consider the ascent of a satellite launch vehicle. Up to $h = 110{,}000$ ft ($t = 120$ sec after launching from the ground), the skin temperature was calculated by continuum flow theory. It was assumed that the skin was made of 0.02-in. stainless steel, with a heat capacity $G = 80$ (ft lb/ft² °R), and that the nose of the vehicle was a cone of 10 deg semiangle. It was further assumed that the nose had been treated with a coating which raised its emissivity (at least in the infrared part of the spectrum) to $\epsilon = 0.8$ in order to take advantage of radiation cooling. The rather thin skin was chosen so that it might heat up quickly to temperatures where the radiation cooling becomes efficient. Quick heating in the initial stages reduces the total amount of heat which is transferred to the skin, and will finally have to be radiated away. With these assumptions, the temperature at a distance of 4 in. from the tip was found to be about 800 R at $t = 120$ sec.[5]

Fig. 5 gives the trajectory data between the altitudes of 110,000 ft and 300,000 ft. These data permitted the evaluation of the local flow data M_1, ρ_1, a_1 and T_1, just outside the boundary layer, from tables of inviscid flow past cones and tables of the standard atmosphere. With these values known as functions of the time, the differential equation [10] was integrated by finite differences.

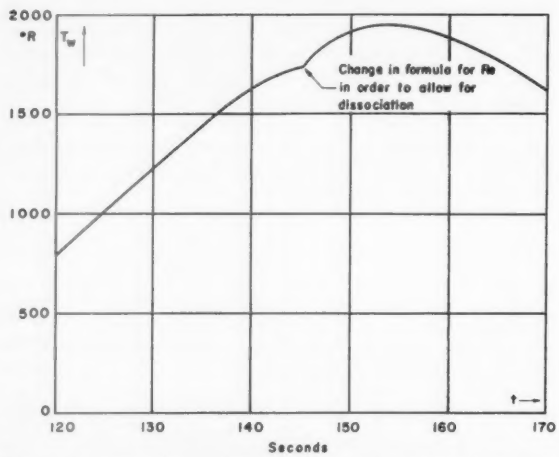

Fig. 6 Conservative estimate for the skin temperature 4-in. from the nose of a 10° cone (calculation based on trajectory data in Fig. 5; specific heat capacity of skin: $G = 80$ ft lb/ft² °R, e.g., 0.02-in. stainless steel)

The result of this calculation is shown in Fig. 6. The maximum temperature is less than 1950 R. This is again high, but still acceptable for stainless steel, particularly at an altitude of 225,000 ft where the dynamic pressure is already small ($q \approx 7$ lb ft^{-2}). The altitude of 225,000 ft is approximately equal to the altitude of 200,000 ft at which we found the peak temperature for the similar trajectory of the first example (Fig. 2).

The temperature curve of Fig. 6 shows a discontinuity of the slope at $t = 145$ sec; a similar discontinuity occurs at the beginning of the curve at $t = 120$ sec. These discontinuities, of course, do not occur in reality. They are caused only by the principle of the present calculation, namely, that the most unfavorable conditions are assumed whenever changes of the behavior of the gas are likely to occur.

(Continued on page 546)

[5] This result has some significance for the selection of stainless steel as a material for the nose cone. A temperature of 800 R is only slightly below the point at which aluminum cannot be safely used, and the temperature is still rising rather rapidly. Hence, we may conclude that aluminum is probably unsuitable for the present purpose, unless the skin is made excessively thick and heavy so that we may rely on it as a heat sink.

Boost Phase Trajectory Analysis Techniques[1]

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Analysis of the boost-phase performance of a rocket-boosted missile generally requires the solution of a set of differential equations with variable coefficients. Analytical methods are difficult and time consuming if not impossible. This paper discusses four numerical approaches to the solution of the equations for a cruciform, uncontrolled missile booster. The first of these, called the "exact" method, will yield results which are as accurate as one cares to make them. The second, referred to as the "semi-exact," assumes that deviations from the flight path are small and oscillatory. With this assumption the solution may be completed in two parts: (a) Computation of the speed-time history and (b) substitution of the speed into the remaining equations. The accuracy for short time oblique launch or for long time vertical launch is as good as the "exact." The third, applicable under the same conditions as the "semi-exact" and referred to as "linear speed-time history," assumes a constant acceleration from launch to the end of boost. The accuracy of this method is very good (on the order of 2 per cent for the terminal speed) provided the thrust-time diagram is nearly trapezoidal. The fourth, called "iterative solution for separation speed," yields an approximate value for the terminal speed with accuracy on the order of 2–4 per cent.

The various uses of the different methods are also discussed as well as techniques for including cross winds, estimating separation speeds and tolerances allowed in estimation of step-wise acceleration. Sample calculations for the three approximate methods are given.

Nomenclature

a = acceleration, fps²
c = speed of sound, fps
C_{N_α} = $\partial C_N/\partial\alpha$ = rate of change of normal force coefficient
C_{M_α} = $\partial C_M/\partial\alpha$ = rate of change of pitching moment coefficient
$C_{M_{\dot\alpha}}$ = $\partial C_M/\partial\dot\alpha$ = rate of change of pitching moment coefficient with $\dot\alpha$
$C_{M_{\dot\theta}}$ = $\partial C_M/\partial\dot\theta$ = rate of change of pitching moment coefficient with $\dot\theta$
C_{D_0} = zero angle of attack drag coefficient
D = drag force, lb
d = general coefficient
e = general coefficient
G = defined in Equation [3.2]
g = gravitational constant, fps²
h = altitude, ft
K_1 = $f_1(m_F/m_0)$, correction constant
K_2 = $f_2(m_F/m_0)$, correction constant
L = perpendicular distance from center of gravity of missile to action line of thrust, ft
M = Mach number = V/C
m = mass, slugs
m_0 = total mass at launch, slugs
m_F = mass of usable propellant, slugs
p = atmospheric pressure, lb/ft²
q = dynamic pressure, lb/ft²
R = difference between assumed and true acceleration, fps²
S = reference area, ft²
S = slant range, ft
T = thrust force, lb
t = time, sec
V = velocity, fps
X = distance measured along launching line, ft
Z = distance normal to flight path, ft
α = angle of attack
γ = flight path angle
ϵ = angle between relative wind and flight path
θ = angle between missile center line and reference plane
λ = angle between reference plane and wind vector
ρ = air density, slug/ft³

Subscripts

E = estimated condition
n = iteration number
m = refers to properties of missile
0 = initial conditions
R = conditions relative to missile
s = separation conditions
t = conditions at time t
$t-1$ = τ = conditions at preceding time considered (not necessarily a unit increment of time such as 1 sec)
w = reference to wind

Superscripts

Dots = derivatives with respect to time, e.g., $\dot X = dx/dt$
Bars = vector quantities

1 Introduction

THE analysis of the performance of a rocket-boosted missile during the boost-phase portion of its flight generally requires that one solve a set of simultaneous differential equations with variable coefficients for a large variety of initial conditions. Analytical methods of solution are formidable if not impossible and consequently ways and means have been developed to accomplish the task with minimum possible effort while maintaining sufficient accuracy and reliability. This paper consists of a collection of four approaches to the problem.

The particular treatment outlined here is for an uncontrolled cruciform missile-booster combination, completely symmetrical with respect to any two normal planes passing through the longitudinal center line. The extension of the methods of unsymmetrical configurations is straightforward since it introduces a few additional terms to the existing equations and adds one more equation of motion for the yaw plane. Extension to the case of a controlled missile requires knowledge of control surface servo characteristics but introduces only one or two additional terms. The additional volume of calculations is another matter.

Since this paper is concerned only with the boost phase performance, the word missile is used in the text to mean the missile-booster combination.

2 Equations of Motion

The equations of motion with respect to the wind axes of a missile symmetrical to two planes which are normal to each

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[2] Engineer.

other and pass through the missile center line are (see Fig. 1)

$$\Sigma F_z = -mV_m\dot{\gamma} \text{ (normal to flight path)} \quad [1]$$

$$\Sigma F_x = m\dot{V}_m \text{ (parallel to flight path)} \quad [2]$$

$$\Sigma M_{cg} = I\ddot{\theta} \text{ (pitch about c.g.)} \quad [3]$$

Summing forces along each of these axes and moments about the center of gravity, then taking account of winds and certain geometrical relations, we arrive at the following set of equations

Normal to flight path

$$mV_m\dot{\gamma} = T \sin(\alpha - \epsilon) + D \sin\epsilon - mg \cos\gamma + C_{N_\alpha}\alpha qS \quad [4]$$

Parallel to flight path

$$m\dot{V}_m = T \cos(\alpha - \epsilon) - D \cos\epsilon - mg \sin\gamma \quad [5]$$

Pitch about c.g. of missile

$$I\ddot{\theta} = -C_{M_\alpha}\alpha qSd - C_{M_{\dot{\theta}}}\dot{\theta}qSd - C_{M_{\dot{\alpha}}}\dot{\alpha}qSd + T \times L \quad [6]$$

Geometry

$$\theta = \alpha + \gamma - \epsilon \quad [7]$$

Wind effects

$$\bar{V}_R = \bar{V}_m - \bar{V}_w \quad [8]$$

$$\tan\epsilon = \frac{V_w \sin(\gamma - \lambda)}{V_m + V_w \cos(\gamma - \lambda)} \quad [9]$$

No equation is necessary for the Y direction since a completely symmetrical missile would undergo the same motion in the XY plane as in the XZ plane with the exception of gravity effects.

These equations are applicable to any flight situation wherein the motion would fit the assumption of small disturbances. The detailed derivation and other assumptions underlying these equations may be found in any good text on airplane stability (e.g., 1, Chap. 10).[3] One tacit assumption, however, is that the missile is free to roll with no cross coupling between roll and directional maneuvers.

The simultaneous solution of Equations [4 through 9] would yield most of the information one might desire about the flight characteristics of the missile. However, due to the nonlinear nature of the aerodynamic coefficients, analytical solution is difficult if not impossible and one is forced to undertake numerical or analog procedures for solutions. The rest of this paper will outline two approaches to the complete solution of the equations and two approaches which by making several assumptions reduce the equations to special cases for specialized results. Only numerical procedures will be considered since analogs involve special techniques too involved for this limited paper.

The first three of the methods to be considered are essentially numerical integration procedures and as such require stepwise (in time) calculation of the various quantities which make up the equations. The fourth method is basically a method by which one obtains a boost-phase terminal speed without stepwise computations.

3 Method of Analysis

A. Exact Analysis

It is admitted that any solution to a set of differential equations other than analytical will not be exact. However, by careful and refined numerical procedures one may attain answers which may be as close to the exact as may be desired for engineering purposes. In view of this, then, "exact" is used here to indicate that numerical solutions can be obtained from Equations [4 through 9] without making additional assumptions.

There are several numerical methods available (2) by which one may obtain solutions to differential equations with variable coefficients. The simplest and the one most often used in boost-phase analysis is the trapezoidal rule, the details of which are given in Appendix 1.

Actually, the exact analysis is seldom undertaken since experience has shown that three simple assumptions lead to a much easier and faster approach without significant loss of accuracy. The new approach will be discussed in the next section.

The exact analysis as outlined here is applicable to any flight which does not violate the assumptions of the derivation of the equations of motion.

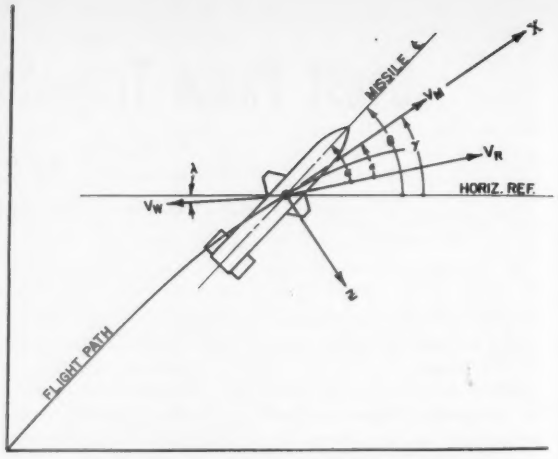

Fig. 1 Coordinate system and sign convention

B. Semi-Exact Analysis

To proceed to the semi-exact method of solution one makes three assumptions as follows:

1 Small oscillatory deviations from the flight path do not affect the velocity of the center of gravity along the flight path. This allows one to use an average value of zero for the angle of attack α.

2 The angle ϵ approaches a negligible value quickly. This assumption is based on a missile which has a large acceleration so that $V_m \gg V_w$ after a short time. Actually, in computing the speed-time history this assumption is not too restrictive.

3 The missile does not deviate greatly from the initial launch angles, or more precisely $\gamma \approx \gamma_0$. This may be put a different way by saying that the gravity drop distance is much less than the slant range distance.

These assumptions allow one to break the solution into two parts: (a) The determination of the speed-time history alone and (b) solution of the pitch and normal force equations using the speed time history.

Using these assumptions we may rewrite Equation [5] as

$$m\dot{V}_m = (T - D) - mg \sin\gamma_0 \quad [5a]$$

and since at $t = 0$, $\alpha = 0$ then

$$\gamma_0 = \theta_0 \quad [7a]$$

and

$$m\dot{V}_m = (T - D) - mg \sin\theta_0 \quad [5b]$$

It should be noted that if a wind condition exists then $\alpha_0 \neq 0$ but may be assumed so for speed-time history calculations under assumption 2. However, the wind component along θ_0 should be added to V_m for computing the drag term.

The procedure from this point is to solve [5b] by the trapezoidal rule to obtain a speed-time history and then sub-

[3] Numbers in parentheses indicate References at end of paper.

stitute the values of V thus obtained in Equations [4, 6] which, taken with [7], will yield a complete solution.

C. Linear Speed-Time History

Since the semi-exact method still requires a tedious stepwise numerical integration to obtain the speed-time it would be expedient to have a faster and simpler method. Such a method has been derived (3) by making the additional assumption that speed is linear with time. In effect this assumption requires a nearly trapezoidal thrust-time curve.

To discuss the method we write Equation [5b] fully as

$$m\dot{V}_m = T - 0.7C_{D_0}pM^2S - m\sin\theta_0 \quad \text{[5c]}$$

where the constant 0.7 is one-half the ratio of specific heats. Since C_{D_0} is usually a complicated function of Mach number a correct approach requires the trial and error procedure of Appendix 1. However, if it is assumed that the speed-time history is linear then one may compute the drag for any given time. Combining the drag with the thrust and gravity terms for corresponding times, one then has an acceleration-time history. Integrating this acceleration-time history by the trapezoidal rule, one obtains a corrected speed-time history which in turn may be combined with the remaining equations to complete the solution. Details are contained in Appendix 2.

The only difficulty in applying this method is in estimating the separation or terminal speed, but a reliable method for this has been developed and will be discussed in the next section.

D. Iterative Solution for Separation Speed

A reliable estimate for the separation speed is required for Section 3-C and is quite often necessary in evaluating the performance of boosters. A simple iterative method has been derived by McCalley (4) based on an approach by Walker and Henke (5). The equation derived by McCalley is

$$V_{n+1} = \frac{\dfrac{Tt_s}{m_0 - \frac{1}{2}m_F}K_1 - gt_s\sin\theta_0}{1 + \dfrac{\rho C_D S(t_s - 1)}{4(m_0 - \frac{2}{3}m_F)}K_2V_n} \quad \text{[10]}$$

where ρ and C_D are selected for the *end point* or estimated separation condition and K_1 and K_2 are selected from Fig. 2. The solution of this equation is, then, merely an evaluation of the constants and iteration of V to convergence. The details underlying Equation [10] are contained in Appendix 3.

To apply Equation [10] one selects the terminal C_D and ρ, estimates the separation time, and computes the quantities indicated to obtain an equation in the form

$$V_{n+1} = \frac{d}{1 + eV_n} \quad \text{[11]}$$

Taking any value of V_n as a start, Equation [11] is computed to yield V_{n+1}, which is then substituted for V_n and the equation evaluated. This procedure continues until convergence is reached.

4 Accuracy

When obtaining numerical solutions to differential equations there is always some loss of accuracy from the possible analytical solution. This is more especially true when using the trapezoidal rule which is, from a mathematical standpoint, rather crude. However, if care is exercised and incremental changes kept small, the errors are negligible from an engineering standpoint. Therefore, it will be assumed that the solution to the exact analysis *is* exact and the other analyses compared with it.

The semi-exact analysis yields practically the same result as the exact, and consequently the error is negligible. In fact, a check was made against data measured in an actual flight to check separation speed only, and the difference between calculated and measured end speeds was minute (6).

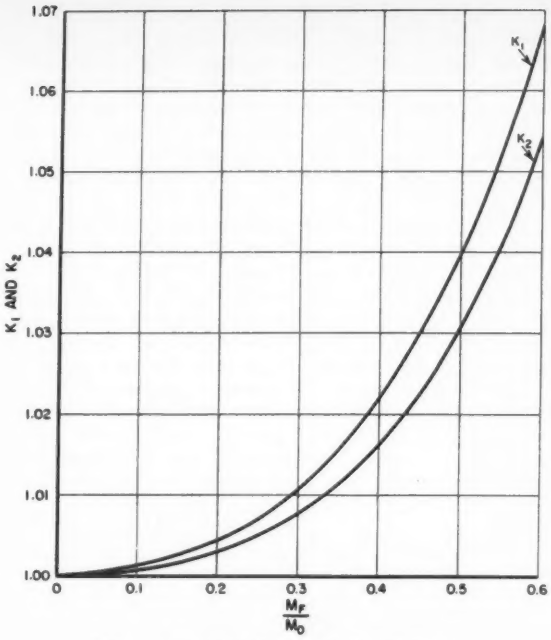

Fig. 2 Correction factors for Equation [5]

An error analysis is very difficult to make on the linear approach to speed-time histories. Numerical comparison has been made however, and the results show that the difference between the semi-exact and the linear speed-time history is generally less than 2 per cent when the estimated separation speed is between 2 and 4 per cent in error (7). For most trajectory analyses the linear speed-time history is sufficiently accurate since a small error in velocity at any given time does not appreciably affect the results.

The McCalley method of computing separation speeds produces errors up to 4 per cent depending on the Mach number. It appears (7) that the error increases with increasing Mach number, which is not surprising since the method assumes time-linear drag. Hence the higher the separation velocity (Mach number) in a given time, the greater the drag-time relation deviates from a straight line and the greater the error.

5 Application

Now that the various methods are in hand it would seem that a statement on the uses of each would be in order. Experience has indicated the area of usefulness to which each method is suited and the types of problems which have been encountered.

As must be evident, the exact or, since the difference is small, the semi-exact analysis is called for whenever the interest is in the actual flight performance of the missile. Either of these will yield time histories of all of the variables in question which are essential in computing air-loads, inertia loads, dispersions, etc. This field of requirements is self-evident and usually no question will arise as to when to use the full analysis.

If one is interested only in the speed-time history then some conflict appears as to the better method. In fact, even when making the semi-exact analysis, the question arises whether an approximate speed-time history, such as obtained from the linear speed-time method, is sufficient for

trajectory analysis. It is the writer's opinion that it is. This opinion is based on the fact that the aerodynamic coefficients do not, throughout the largest portion of the boost-phase, change radically with Mach number. Thus, if one has a small speed error at some step, it is obvious that the forces computed are not greatly different from the exact. The error thus generated is more than compensated for by the saving of time and expense. However, one must judge for himself on this point.

There are times when the separation speed is of the utmost importance. For example, a certain minimum speed is required for engine starting and there may be a question as to whether the booster impulse is sufficient to produce this speed. In such a problem the exact or semi-exact speed history as opposed to the linear speed-time history is an absolute must if nearly exact knowledge of separation speed is to be gained.

Whenever the problem of booster design arises, there are several ways to attack it. First, by using the McCalley method one may determine a general area of impulse necessary to reach a given speed. The impulse may then be translated into more exact speeds by using one of the more refined methods. Furthermore, one may show the effects of changes in the booster and missile parameters by using the McCalley equation. Thus, in an initial design study the McCalley approach is extremely useful in setting approximate boundaries. All of this presupposes that the propellant characteristics are known or estimable as they relate to physical dimensions, gas pressures, etc. If one is starting with no knowledge of propellant characteristics other than specific impulse, then a more refined approach, such as that developed by Hawley and Fenton (8) is required. Booster design is outside the scope of this paper and will not be discussed further.

The McCalley method has demonstrated its usefulness in determining *changes* in separation speed with changes of the various parameters. These differences are always of the right order of magnitude and the right direction, and are very reliable.

6 Techniques

There are certain details which arise during the actual calculations which are sometimes confusing. This section will try to clarify a few of the more important ones.

A. Wind Effects

First consideration will be given to wind effects and how these are included in the various analyses. When using the exact analysis one must account for the wind at every step. Obviously this amounts to solving Equations [1 through 6] without modification, a time consuming task. It should be carefully noted that the relative velocity V_R is used in computing the aerodynamic terms. To illustrate, take Equation [5] and write in full

$$m\dot{V}_m = T\cos(\alpha - \epsilon) - C_D\frac{V_R^2}{2}\rho S\cos\epsilon - mg\sin\gamma \ldots [12]$$

Thus, the $\dot{V}_m$ refers to acceleration relative to earth, while the V_R refers to missile velocity relative to the air.

The semi-exact method may fortunately be handled a little differently. Since the speed of the missile becomes much greater than the wind in a very short time then one is justified in neglecting the angles α and ϵ in the computation of the speed-time history. However, one must add the wind component along the line γ_0 to obtain the drag at each time-wise step. When substitution is made into the remaining equations of motion then allowance must be made for the change in angle of attack due to wind.

In the linear speed-time analysis one must assume a velocity history based on an average acceleration. To compute the drag the relative velocity is used, so that one must add at every time-wise step the component of the wind along γ_0 to the speed-time history computed from the average acceleration. The same consideration of angle of attack changes must be given as in the semi-exact method when complete solutions are desired.

The McCalley equation makes no provision for wind effects but it may be considered that the equation always yields the relative velocity as the solution. That is, the V obtained by iteration already contains a wind component.

B. Nonlinear Pressure- or Density-Altitude Relations

In setting up the linear speed-time analysis for solution on digital equipment, one encounters the difficulty of nonlinear pressure-altitude or density-altitude relations. If, however, these relationships are expanded in a Taylor series about the altitude of the launching site, then by taking the first two terms the pressure (or density) may be determined approximately in linear form. It has been found that no substantial error is introduced up to an altitude of about 5000 ft above the launching site. The same sort of approximation may be made for the speed of sound.

C. Estimated Value of Acceleration

In working the speed histories using the semi-exact analysis and the trapezoidal rule it has been found that a sizable error may be allowed in the estimated value of acceleration (or as notated in the Appendix, $\ddot{X}$). The reason for this is apparent through examination of the following:

Let $\ddot{X}_t$ be the correct value of the acceleration at the end of the next time increment, $\ddot{X}_E$ the estimated value, and R the difference. Then

$$\dot{X}_t = \frac{\ddot{X}_t + \ddot{X}_{t-1}}{2}\Delta t + \dot{X}_{t-1} = \frac{\ddot{X}_t + \ddot{X}_E + R}{2}\Delta t + \dot{X}_{t-1}$$

$$= \frac{\ddot{X}_t + \ddot{X}_E}{2}\Delta t + \dot{X}_{t-1} + \frac{R}{2}\Delta t$$

$$X_t = \frac{\dot{X}_t + \dot{X}_{t-1}}{2}\Delta t + X_{t-1} =$$

$$\frac{\frac{\ddot{X}_t + \ddot{X}_E}{2}\Delta t + 2\dot{X}_{t-1} + \frac{R}{2}\Delta t}{2}\Delta t + X_{t-1}$$

$$= \frac{\ddot{X}_t + \ddot{X}_E}{4}\Delta t^2 + \dot{X}_{t-1}\Delta t + X_{t-1} + \frac{R}{4}\Delta t^2$$

This shows that the value of X_t is in error by the amount of $(R/4)\Delta t^2$. If $\Delta t = 0.1$ sec and $R = 100$ fps^2, then the error in X_t is only 0.25 ft with an even smaller change in altitude. The error in the speed $\dot{X}_t$ is $(R/2)\Delta t$ which, using the same numbers as before, is 5 fps. The combination of the small change in Mach number and altitude shows that a large error in $\ddot{X}_E$ is not serious if small time increments are used.

Appendix 1

Numerical Integration by Trapezoid Rule

Assume the following equation is to be solved

$$\ddot{X} = b\dot{X} + eX + d \ldots\ldots\ldots\ldots [1.1]$$

where the b, e, and d are, in general, functions of X and t; and assume that we have reached the solution of the equation up to some time $t = \tau$.

By extrapolating the past history, or by any means available, one estimates the value of $\ddot{X}$ after some small time increment $(t - \tau)$ as $\ddot{X}_t$. If the time increment is small enough and the functions are behaving smoothly, then an average value of $\ddot{X}$ may be calculated for the interval as

$$\ddot{X}_{avg} = \frac{\ddot{X}_t + \ddot{X}_\tau}{2} \ldots\ldots\ldots\ldots [1.2]$$

Then the value of $\dot{X} = \dot{X}_t$ at the end of the interval is approximately

$$\left.\begin{aligned}\dot{X}_t &= \ddot{X}_{avg}(t - \tau) + \dot{X}_\tau \\ &= \frac{\ddot{X}_t + \ddot{X}_\tau}{2}(t - \tau) + \dot{X}_\tau\end{aligned}\right\} \quad \ldots\ldots\ldots [1.3]$$

and the value of $X = X_t$ is

$$\left.\begin{aligned}X_t &= \dot{X}_{avg}(t - \tau) + X_\tau \\ &= \frac{\dot{X}_t + \dot{X}_\tau}{2}(t - \tau) + X_\tau\end{aligned}\right\} \quad \ldots\ldots\ldots [1.4]$$

The values of X_t and $\dot{X}_t$ obtained from [1.3 and 1.4] are then multiplied by b and e, which are selected for $t = t$ and $x = x_t$, and added to the value of d selected the same way. The sum thus obtained, called the *calculated* value of $\ddot{X}_t$, is compared to the estimated value of $\ddot{X}_t$, and if agreement is attained one proceeds to the next time increment. If agreement is not realized, then $\ddot{X}_t$ is estimated again until the estimated and calculated values of $\ddot{X}_t$ are very nearly the same.

If in Equation [1.1] b, e and d are constants or are functions of t only, then the process becomes iterative, i.e., the value of $\ddot{X}_t$ obtained from calculation is used as the estimated value of $\ddot{X}_t$. The process is usually convergent. Obviously, if b, e and d are constants, then an analytical solution is straightforward.

Appendix 2

Linear Method of Computing Speed-Time Histories

Assume the following:

1 The speed-time history is linear.
2 The separation speed, V_s.
3 The separation time, t_s.

With these assumptions one proceeds by calculating an average acceleration as

$$a_{avg} = \frac{V_s}{t_s} \quad \ldots\ldots\ldots [2.1]$$

Then compute the speed

$$V(t) = a_{avg}\, t + V_0 \quad \ldots\ldots\ldots [2.2]$$

and the slant range

$$S(t) = \tfrac{1}{2}a_{avg}t^2 + V_0 t + S_0$$

The altitude h, is then calculated from $S(t)$ and the speed of sound and pressure determined as functions of h as follows

$$h = S(t)\sin\theta \quad \ldots\ldots\ldots [2.3]$$

$$c = f_1(h) \quad \ldots\ldots\ldots [2.4]$$

$$p = f_2(h) \quad \ldots\ldots\ldots [2.5]$$

The drag D as a function of time is then easily found by the following steps:

1 Compute the Mach number $M(t) = V(t)/c$
2 Select the drag coefficient corresponding to $M(t)$ at each time interval.
3 Complete the drag calculation by the equation

$$D(t) = 0.7 C_D p M^2 S \quad \ldots\ldots\ldots [2.6]$$

where the 0.7 is one-half the ratio of specific heats for air and S is the reference area.

The remainder of the speed history is just a question of evaluating the following equation and applying the trapezoid rule

$$a(t) = \frac{T(t)}{M(t)} - \frac{D(t)}{M(t)} - g\sin\theta \quad \ldots\ldots\ldots [2.7]$$

Appendix 3

McCalley Equation

The McCalley equation is based on a method developed by Walker and Henke wherein the drag is assumed to be linear with time. Under this assumption plus the additional one that the mass varies linearly with time, Walker obtains

$$V = \frac{G}{2} + \frac{G}{2}\sqrt{1 + \left(\frac{4}{G}\right)\left[\frac{Tt_s}{m_F}\ln\left(1 - \frac{m_F}{m_0}\right) + gt_s\sin\theta\right]} \quad [3.1]$$

where

$$G = \frac{2m_0\left(\frac{m_F}{m_0}\right)^2}{\rho C_D S t_s\left[\frac{m_F}{m_0} + \ln\left(1 - \frac{m_F}{m_0}\right)\right]} \quad \ldots\ldots [3.2]$$

McCalley's contribution comes about by restating the Walker equation as

$$V_{n+1} = \frac{\frac{-Tt_s}{m_F}\ln\left(1 - \frac{m_F}{m_0}\right) - gt_s\sin\theta}{1 - \frac{\rho S C_D t_s m_0}{2m_F^2}\left[\frac{m_F}{m_0} + \ln\left(1 - \frac{m_F}{m_0}\right)\right]} V_n \quad [3.3]$$

and then expanding the logarithm terms in a series. Taking only the first two (linear) terms and applying correction factors McCalley derives the expression

$$V_{n+1} = \frac{\frac{Tt_s}{m_0 - \frac{1}{2}m_F}K_1 - gt_s\sin\theta}{1 + \frac{\rho C_D S t_s}{4(m_0 - \frac{2}{3}m_F)}K_2 V_n} \quad \ldots\ldots [3.4]$$

Observation of drag calculations made under more exact conditions has led to the conclusion that the drag is linear not from $t = 0$ but from $t = 1$ sec. This fact in turn leads to a modification of Equation [4] which is more nearly in keeping with the physical situation

$$V_{n+1} = \frac{\frac{Tt_s}{m_0 - \frac{1}{2}m_F}K_1 - gt_s\sin\theta}{1 + \frac{\rho C_D S(t_s - 1)}{4(m_0 - \frac{2}{3}m_F)}K_2 V_n} \quad \ldots\ldots [3.5]$$

The correction factors K_1 and K_2 are given in Fig. 2.

It should be noted that the value of T shown here is an average one which will give the proper impulse between $t = 0$ and $t = t_s$.

Appendix 4

Sample Calculations

Since this paper is concerned primarily with the approximate methods of obtaining the speed-time history for use in trajectory analyses or with obtaining an estimated terminal speed and not with a complete trajectory study, calculations have been prepared to illustrate the techniques of the approximations only. The thrusts, masses, times, etc., do not necessarily represent any known missile but are selected to demonstrate the techniques.

The following data were used in all three sample calculations

Mass, slugs	m	$= 200 - 25t$
Thrust, pounds	T	$= 9{,}000{,}000t,\ 0 \le t \le 0.01$ sec
		$= 90{,}000,\ 0.01 \le t \le 1.95$ sec
		$= 3{,}600{,}000 - 1{,}800{,}000t,\ 1.95 \le t \le 2.0$ sec
Drag coefficient	C_{D_0}	$= 0.5,\ 0 \le M \le 0.8$
		$= 0.25M + 0.3,\ 0.8 \le M \le 1.2$
		$= 0.6,\ 1.2 \le M$
Reference area	S	$= 4.0$ ft^2

Atmospheric pressure $p = 2116 - 0.0724h$ lb/ft², $0 \leq h < 5000$ ft

Speed of sound $c = 1149 - 0.00355h$ fps, $0 \leq h < 5000$ ft

Launch angle $\theta_0 = \gamma_0 = 45$ deg

Wind speed $V_w = 50$ fps (headwind)

Hence $V_R = \sqrt{V_m^2 + V_w^2 + 2V_mV_w \cos\theta}$, fps

$\lambda = 0$

$t_{zest} = 1.95$ sec

The sample calculations for the semi-exact method are shown in Table 1 and for the linear speed-time history in Table 2. The McCalley approximation is shown at right.

Note that the acceleration used in the linear speed-time history was obtained from the McCalley approximation as follows

$$a = \frac{V_{\text{McCalley}} - V_w \cos\theta_0}{t_s} = \frac{960.04 - 35.35}{1.95} = 474.2 \text{ fps}^2$$

McCalley Approximation

$$V_{n+1} = \frac{\dfrac{Tt}{m_0 - \frac{1}{2}m_F} K_1 - gt_s \sin\theta_0}{1 + \dfrac{\rho C_D S(t_s - 1)}{4(m_0 - \frac{3}{4}m_F)} K_2 V_n}$$

$\rho = 0.002203$ slugs/ft³ $\quad g = 32.2$ fps²

$C_D = 0.51 \quad \sin\theta_0 = 0.707$

$Tt = 175{,}500$ lb-sec $\quad \dfrac{m_F}{m_0} = 0.25$

$t_s = 1.95$ sec $\quad K_1 = 1.0075$

$S = 4$ ft² $\quad K_2 = 1.005$

$m_0 = 200$ slugs

$m_F = 50$ slugs

Table 1 Semi-exact speed-time history

(1) t, sec	(2) τ, sec	(3) $\dot{V}_m$(est.), fps²	(4) ΔV_m, fps, $[(3)_t + (22)_\tau] \times [(t-\tau)/2]$	(5) V_{m_t}, fps, $(4)_t + (5)_\tau$	(6) ΔS, ft, $[(5)_t + (5)_\tau] \times [(t-\tau)/2]$	(7) S_t, ft, $(6)_t + (7)_\tau$	(8) h, ft, (7) $\sin\theta_0$	(9) c, fps	(10) p, lb/ft²	(11) V_R, fps, $[V_m^2 + V_w^2 + 2V_mV_w \times \cos\theta_0]^{1/2}$
0		0	0	0	0	0	0	1149	2116	50
0.1	0	430	21.5	21.5	1.08	1.08	0	1149	2116	66.95
0.2	0.1	436	43.30	64.8	3.29	4.37	3.09	1149	2116	106.21
0.3	0.2	444	44.13	108.93	8.69	13.06	9.23	1149	2116	148.55
0.4	0.3	451	44.72	153.65	13.13	26.20	18.52	1149	2115	192.41
0.5	0.4	455	45.27	198.92	17.63	43.83	30.99	1149	2114	263.92
0.6	0.5	463	45.89	244.81	22.19	66.01	46.67	1149	2113	282.31
0.7	0.6	470	46.64	291.38	26.81	92.82	65.62	1149	2111	328.64
0.8	0.7	477	47.30	338.68	31.50	124.32	87.90	1149	2110	375.70
0.9	0.8	481	47.82	386.50	36.26	160.58	113.53	1149	2108	423.33
1.0	0.9	488	48.50	435.00	41.08	201.65	142.61	1148	2106	471.68
1.1	1.0	494	49.13	484.13	45.96	247.61	175.11	1148	2103	520.68
1.2	1.1	501	49.82	533.95	50.90	298.51	211.11	1148	2101	570.40
1.3	1.2	509	50.57	584.52	55.92	354.43	250.66	1148	2098	620.88
1.4	1.3	516	51.27	635.79	61.02	415.45	293.81	1148	2095	672.07
1.5	1.4	523	51.98	687.77	66.18	481.63	340.61	1148	2091	723.98
1.6	1.5	531	52.78	740.55	71.42	553.05	391.12	1148	2088	776.71
1.7	1.6	539	53.52	794.07	76.73	629.78	445.39	1147	2084	830.18
1.8	1.7	544	54.15	848.22	82.11	711.89	503.46	1147	2080	884.28
1.9	1.8	554	55.04	903.26	87.57	799.46	565.39	1147	2075	939.28
1.95	1.9	558	27.81	931.07	45.86	845.32	597.64	1147	2072	967.07
2.0	1.95	−38	13.00	944.07	46.88	892.20	630.97	1147	2070	980.06

(12) M (11) / (9)	(13) M^2 (12)²	(14) qs, lb .7S × (10) × (13)	(15) C_D	(16) D, lb, (14) × (15)	(17) mass, slugs	(18) Thrust, lb	(19) T/m, fps² (18) × (17)	(20) D/m, fps² (16) × (17)	(21) $g \sin\theta_0$, fps² 32.2 $\sin\theta_0$	(22) $\dot{V}_m$, fps² (19) − (20) − (21)
0.0435	0.00189	11.20	0.5	5.60	200	0	0	0.028	22.77	on launcher
0.058	0.0034	20.14	0.5	10.07	197.5	90,000	455.70	0.0510	22.77	432.88
0.0924	0.00854	50.60	0.5	25.30	195	90,000	461.54	0.130	22.77	438.64
0.129	0.0166	98.35	0.5	49.18	192.5	90,000	467.53	0.255	22.77	444.51
0.168	0.0282	167.00	0.5	83.50	190	90,000	473.68	0.439	22.77	450.47
0.206	0.0424	250.97	0.5	125.48	187.5	90,000	480.00	0.669	22.77	456.56
0.246	0.0605	357.95	0.5	178.98	185	90,000	486.49	0.967	22.77	462.75
0.286	0.0818	483.50	0.5	241.75	182.5	90,000	493.15	1.325	22.77	469.06
0.327	0.1069	631.57	0.5	315.79	180	90,000	500.00	1.754	22.77	475.48
0.368	0.1354	799.18	0.5	399.59	177.5	90,000	507.04	2.251	22.77	482.02
0.411	0.1689	995.97	0.5	497.98	175	90,000	514.29	2.846	22.77	488.67
0.454	0.2061	1213.60	0.5	606.80	172.5	90,000	521.74	3.518	22.77	495.45
0.497	0.2470	1464.82	0.5	732.41	170	90,000	529.41	4.308	22.77	502.33
0.541	0.2927	1719.44	0.5	859.72	167.5	90,000	537.31	5.133	22.77	509.41
0.585	0.3422	2007.35	0.5	1003.68	165	90,000	545.45	6.083	22.77	516.60
0.631	0.3982	2331.38	0.5	1165.69	162.5	90,000	553.85	2.173	22.77	524.61
0.677	0.4583	2679.40	0.5	1339.70	160	90,000	562.50	8.373	22.77	531.36
0.724	0.5242	3058.81	0.5	1529.40	157.5	90,000	571.43	9.711	22.77	538.95
0.771	0.5944	3461.79	0.5	1730.90	155	90,000	580.64	11.117	22.77	546.75
0.819	0.6708	3897.35	0.505	1968.16	152.5	90,000	590.16	12.905	22.77	554.48
0.842	0.7090	4079.59	0.510	2080.59	151.25	90,000	595.05	13.756	22.77	558.52
0.854	0.7293	4227.02	0.514	2172.69	150	0	0	14.456	22.77	−37.26

Table 2 Linear speed-time history

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
		$V_m = at$	$S = \frac{1}{2}at^2$	$h = S \sin \theta_0$			V_R	M		qs, lb
t, sec	a, fps^2	(2) × (1), fps	$\frac{(3) \times (1)}{2}$, ft	(4) × 0.707, ft	c, fps	p, lb/ft^2	(3) + 35.35, fps	(8)/(6)	M^2 (9)^2	2.8 × (7) × (10)
0	0	0	0	0	1149	2116	35.35	0.031	0.00096	5.69
0.1	474.2	47.42	2.371	1.676	1148.994	2115.879	82.77	0.0720	0.0052	30.807
0.2	474.2	94.84	9.484	6.705	1148.976	2115.515	130.19	0.1133	0.0128	75.820
0.3	474.2	142.26	21.339	15.087	1148.946	2114.908	177.61	0.1546	0.0239	141.530
0.4	474.2	189.68	37.936	26.821	1148.905	2114.058	225.03	0.1959	0.0384	227.304
0.5	474.2	237.10	59.275	41.907	1148.851	2112.966	272.45	0.2371	0.0562	332.496
0.6	474.2	284.52	85.356	60.347	1148.786	2111.631	319.87	0.2784	0.0775	458.224
0.7	474.2	331.94	116.179	82.139	1148.708	2110.054	367.29	0.3197	0.1022	603.813
0.8	474.2	379.36	151.744	107.283	1148.619	2108.233	414.71	0.3611	0.1304	769.758
0.9	474.2	426.78	192.051	135.780	1148.518	2106.170	462.13	0.4024	0.1619	954.769
1.0	474.2	474.20	237.100	167.630	1148.405	2103.864	509.55	0.4437	0.1969	1159.90
1.1	474.2	521.62	286.891	202.832	1148.280	2101.315	556.97	0.4850	0.2352	1383.84
1.2	474.2	569.04	341.424	241.387	1148.143	2098.524	604.39	0.5264	0.2771	1628.20
1.3	474.2	616.46	400.699	283.294	1147.994	2095.490	651.81	0.5678	0.3224	1891.64
1.4	474.2	663.88	464.716	328.554	1147.834	2092.213	699.23	0.6092	0.3711	2173.98
1.5	474.2	711.30	533.475	377.167	1147.661	2088.693	746.65	0.6506	0.4233	2475.60
1.6	474.2	758.72	606.976	429.132	1147.477	2084.931	794.07	0.6920	0.4789	2795.73
1.7	474.2	806.14	685.219	484.450	1147.280	2080.926	841.49	0.7335	0.5380	3134.71
1.8	474.2	853.56	768.204	543.120	1147.072	2076.678	888.91	0.7749	0.6005	3491.73
1.9	474.2	900.98	855.931	605.143	1146.852	2072.188	936.33	0.8164	0.6665	3867.12
1.95	474.2	924.69	901.570	637.410	1146.737	2069.852	960.04	0.8372	0.7009	4062.13

(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)
	D			D/m	T/m	$g \sin \theta$	a	ΔV	V_m
C_D	(11) × (12), lb	T, lb	m, slugs	(13)/(15), fps^2	(14)/(15), fps^2	32.2 × .707, fps^2	(17) − (16) −(18), fps^2	$\frac{(19)_t + (19)_\tau}{2}(t - \tau)x$	(20)$_t$ + (21)$_\tau$, fps
0.5	2.84	0	200				0	0	0
0.5	15.40	90,000	197.5	0.0780	455.70	22.7654	432.86	21.6	21.6
0.5	37.91	90,000	195	0.1944	461.54	22.7654	438.58	43.57	65.17
0.5	70.77	90,000	192.5	0.3676	467.53	22.7654	444.40	44.15	109.32
0.5	113.65	90,000	190	0.5982	473.68	22.7654	450.32	44.74	154.06
0.5	166.25	90,000	187.5	0.8867	480.00	22.7654	456.35	45.33	199.39
0.5	229.11	90,000	185	1.2384	486.49	22.7654	462.49	45.94	245.33
0.5	301.91	90,000	182.5	1.6543	493.15	22.7654	468.73	46.56	291.89
0.5	384.88	90,000	180	2.1382	500.00	22.7654	475.10	47.19	339.08
0.5	477.38	90,000	177.5	2.6895	507.04	22.7654	481.59	47.83	386.91
0.5	579.95	90,000	175	3.3140	514.29	22.7654	488.21	48.49	435.40
0.5	691.92	90,000	172.5	4.0111	521.74	22.7654	494.96	49.16	484.56
0.5	814.10	90,000	170	4.7888	529.41	22.7654	501.86	49.84	534.40
0.5	945.82	90,000	167.5	5.6467	537.31	22.7654	508.90	50.54	584.94
0.5	1086.99	90,000	165	6.5878	545.45	22.7654	516.10	51.25	636.19
0.5	1237.80	90,000	162.5	7.6172	553.85	22.7654	523.48	51.98	688.17
0.5	1397.87	90,000	160	8.7367	562.50	22.7654	531.00	52.72	740.89
0.5	1567.36	90,000	157.5	9.9515	571.43	22.7654	538.71	53.49	794.38
0.5	1745.87	90,000	155	11.2637	580.65	22.7654	546.62	54.27	848.65
0.504	1949.03	90,000	152.5	12.7805	590.16	22.7654	554.61	55.06	903.71
0.509	2067.62	90,000	151.25	13.6702	595.04	22.7654	558.60	27.83	931.54

$$V_{n+1} = \frac{\frac{(175{,}500)(1.0075)}{175} - (32.2)(1.95)(0.707)}{1 + \frac{0.002203 \times 0.51 \times 4(1.95 - 1)}{4(166.67)}(1.005)V_n}$$

$$= \frac{1010.37 - 44.39}{1 + \frac{0.0042907}{666.68}V_n} = \frac{965.98}{1 + 0.00000644V_n}$$

$V_1 = 965.98$ fps

$$V_2 = \frac{965.98}{1.00622} = 959.63 \text{ fps}$$

$$V_3 = \frac{965.98}{1.00618} = 960.05 \text{ fps}$$

$$V_4 = \frac{965.98}{1.006183} = 960.04 \text{ fps}$$

References

1 Perkins, Courtland D., and Hage, Robert E., "Airplane Performance Stability and Control," John Wiley, 1949.

2 Scarborough, J. B., "Numerical Mathematical Analysis," 2nd ed., The Johns Hopkins University Press, Baltimore, 1950.

3 Brown, R. C., "Preliminary Boost-Phase Performance of the TALOS 6bW1 Weapon," McDonnell Aircraft Corporation Memo 4712, AWM-83, Dec. 1954.

4 McCalley, R. B., "A Simplified Method of Making Approximate Boost Velocity Calculations," APL/JHU Engineering Memorandum 1572, Sept. 1953.

5 Letter from J. H. Walker and J. C. Henke to J. F. R. Floyd on "Nomograph to Determine Booster Terminal Velocity," May 27, 1949.

6 West, C. D., "Analytical Determination of S/N 48 Boost-Phase Separation Speed," APL/JHU Eng. Memo. 2390, Dec. 1955.

7 West, C. D., "Comparison of Methods for Computing Separation Velocities," APL/JHU Eng. Memo. 2158, Feb. 1955.

8 Hawley, W. W., and Fenton, W. H., "A Method for Determining Booster Rocket Requirements," APL/JHU CF-2350, March 1955.

Intermittent Detonation as a Thrust-Producing Mechanism[1]

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The feasibility of a reaction device operating on intermittent gaseous detonation waves is considered. The results of a simplified theoretical analysis are presented and discussed. Preliminary experiments were conducted to determine the impulse derived from a single detonation wave and to investigate some of the more influential parameters: These tests were effected by suspending the detonation tube as a pendulum. A cyclic detonation tube was designed and operated utilizing hydrogen-air mixtures. Measurements of thrust, fuel flow, air flow, and temperatures were obtained over a range of operating conditions. Specific impulses of over 2100 sec were realized, which was in good agreement with the predicted performance.

Nomenclature

a = speed of sound
A = area
f = per cent fuel by volume
F = thrust
I = specific impulse, lb thrust/lb fuel per second
L = length
m = molecular weight
M = Mach number
P = pressure
Q = heat release
R = universal gas constant
T = temperature
t = time
t_D = time for detonation to traverse length L
t_r = time for rarefaction to traverse length L
t_f = time to introduce fresh charge
t_c = time for one cycle
V = velocity
w_f = weight flow of fuel per unit time
w_{f_c} = weight of fuel per cycle
w_0 = weight flow of oxygen per unit time
w_{0_c} = weight of oxygen per cycle
γ = ratio of specific heats
ρ = density

Subscripts

0 = stagnation condition or oxygen
1 = conditions in unburned gas
2 = conditions in burned gas
3 = conditions at plateau behind detonation wave
f = fuel

Introduction

IN THE course of investigations on gaseous detonative combustion (1, 2)[5] it occurred to the authors that an engine operating intermittently on detonation waves might afford some advantages. Consequently, a theoretical analysis was made in 1952 in order to investigate the feasibility of such a cycle (3). These results indicated that, in general, very high specific thrusts (thrusts per unit combustion chamber area) could be attained but at the expense of specific impulse. However, in the case of hydrogen-air mixtures the results were the reverse; high specific impulses were indicated but at relatively low specific thrust. It appears that an intermittent detonation engine would offer many advantages. Selection of the proper fuel could materially affect the operating characteristics so that a range of applications is possible. Also the engine would be capable of static thrust as well as efficient operation at supersonic velocities. Hence, it could bridge the gap between the pulsejet and ramjet. Mechanically, the engine could be extremely simple with few or no rotating parts.

On the basis of this preliminary analysis, the research program described herein was initiated for the purpose of exploring experimentally the possibility and feasibility of an engine operating on intermittent detonative combustion. At the time this work was initiated, no information was available on any previous work on this subject. Subsequently, it was found that Hoffman (4) of Germany had successfully operated an engine on intermittent detonation in 1941. A summary of his work was included in an earlier progress report (5).

Analytical work relating to this subject has been reported by Bitondo, Bollay and Kendrick (6, 7). In general, their predicted results lay in the intermediate specific impulse and specific thrust ranges. They conclude that a pulsating detonation engine has profitable application to helicopter propulsion.

Analysis

As mentioned earlier, theoretical calculations on the performance of a reaction device operating on intermittent detonation waves indicated favorable aspects of such a cycle if it could be realized physically. It is intended to review briefly these results as well as some of the fundamental characteristics of detonative combustion.

A detonation wave is conventionally treated as a shock wave followed by combustion. If we consider a stationary gaseous detonation wave in a constant area duct, the hydrodynamic analysis may be readily formulated and is merely the problem of heat addition to a one-dimensional stream. Referring to Fig. 1, the conservation equations and an equation of state may be written as

Momentum: $$P_1 + \rho_1 V_1^2 = P_2 + \rho_2 V_2^2 \quad [1]$$

Mass: $$\rho_1 V_1 = \rho_2 V_2 \quad [2]$$

State: $$P = \rho \frac{R}{m} T \quad [3]$$

Rearranging the momentum equation and introducing the equation of state and Mach number

$$\frac{P_2}{P_1} = \frac{1 + \gamma_1 M_1^2}{1 + \gamma_2 M_2^2} \quad [4]$$

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[5] Numbers in parentheses indicate References at end of paper.

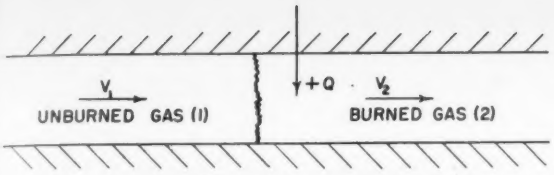

Fig. 1 Detonation wave in a constant area duct

where M_1 will be referred to as the Mach number of detonation. The hydrodynamic analysis predicts that M_2, the Mach number of the burned gases relative to the front, may be subsonic, sonic or supersonic. These processes correspond, respectively, to strong detonation, Chapman-Jouguet detonation and weak detonation. The latter type can be shown to violate entropy considerations while strong detonation has never been observed in the stable state. It is an experimental fact that the Chapman-Jouguet detonation is the type experienced, although under certain conditions it should be possible to generate stable, strong detonations (1, 8). In view of these considerations, $M_2 = 1$ and the pressure ratio across the detonation wave becomes

$$\frac{P_2}{P_1} = \frac{1 + \gamma_1 M_1^2}{1 + \gamma_2} \quad \ldots\ldots [5]$$

The ratios of temperature, density and stagnation pressure across the detonation wave may be readily derived and are

$$\frac{T_2}{T_1} = \frac{m_2}{m_1} \cdot \frac{\gamma_2}{\gamma_1} \cdot \frac{1}{M_1^2} \left[\frac{1 + \gamma_1 M_1^2}{1 + \gamma_2}\right]^2 \quad \ldots\ldots [6]$$

$$\frac{\rho_2}{\rho_1} = \frac{\gamma_1}{\gamma_2} \cdot M_1^2 \left(\frac{1 + \gamma_2}{1 + \gamma_1 M_1^2}\right) \quad \ldots\ldots [7]$$

and

$$\frac{P_{02}}{P_{01}} = \left[\frac{1 + \gamma_1 M_1^2}{1 + \gamma_2}\right] \frac{\left(\frac{\gamma_2 + 1}{2}\right)^{\gamma_2/(\gamma_2 - 1)}}{\left(1 + \frac{\gamma_1 - 1}{2} M_1^2\right)^{\gamma_1/(\gamma_1 - 1)}} \quad \ldots\ldots [8]$$

In the case of a flame tube the pressure established behind the detonation wave, as indicated by Equation [5] will be modified by trailing rarefaction waves. Hence, the pressure P_2 will be reduced to a plateau pressure P_3. This plateau pressure is related to the peak pressure by the relation

$$\frac{P_3}{P_1} = \frac{P_2}{P_1}\left[1 - \frac{\gamma_2 - 1}{2} M_{2c}\right]^{2\gamma_2/(\gamma_2 - 1)} \quad \ldots\ldots [9]$$

where M_{2c} is the Mach number of the burned gases relative to a fixed point on the flame tube. For Chapman-Jouguet detonation, this is a subsonic Mach number whereas for shock waves it could be either subsonic or supersonic.

As can be seen from the relations derived, the fundamental parameter in expressing the changes across a detonation wave is the Mach number of detonation. Consequently, a general range of the pressures and temperatures involved may be obtained by plotting the ratios against the Mach number of detonation if simplifications are made as to the changes in γ and molecular weight. Such a plot is shown in Fig. 2 wherein it was assumed that $\gamma_1 = 1.4$, $\gamma_2 = 1.15$, and $m_2/m_1 = 1.0$. Typical values of the Mach number of detonation range from about 3.0 to 10.

The above characteristics are, of course, influential in the thrust-producing ability of intermittent detonation waves. Let us consider a detonation tube of uniform cross-sectional area A and length L. A spark plug is located at the closed end while the other end is open. The intermittent detonation cycle visualized is:

1 Introduction of the gaseous detonable mixture.

2 Initiation of a flame front at the closed end by energization of the spark plug.

3 Development of a detonation wave from the flame front.

4 Reflection of rarefaction waves as the detonation wave reaches the open end of the tube.

5 Gradual exhausting of the burned gases as the rarefaction waves move upstream and reflect from the closed end as a further rarefaction. Eventually, the tube reaches subatmospheric pressures so that compression waves are reflected from the open end.

6 Introduction of the fresh charge for the next cycle.

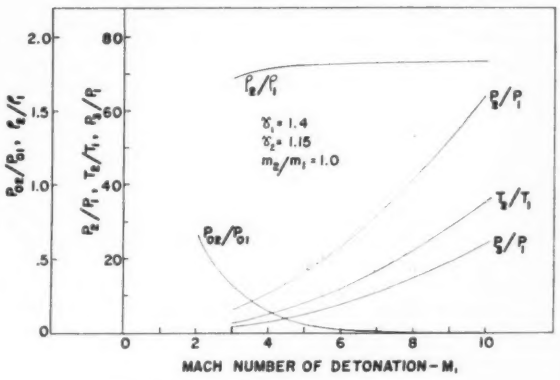

Fig. 2 Properties of detonation waves

A detailed analysis of the unsteady flow thermodynamic cycle would be exceedingly complex and lengthy. Furthermore, there would still be ambiguity because the mathematical description of the transition of flame front to detonation cannot be readily formulated. Accordingly, a number of simplifying assumptions were made in the original analysis in order to obtain an engineering evaluation of an intermittent detonation engine. These assumptions were:

1 Chapman-Jouguet detonation is established immediately at the closed end of the tube.

2 The rarefaction wave returns as a discontinuity and at sonic velocity corresponding to state 2.

3 This original rarefaction wave reduces the pressure level of the tube to atmospheric pressure so that all subsequent reflections are neglected.

4 Introduction of the fresh charge takes place at atmospheric pressure.

5. No valving or frictional losses are involved.

In view of these simplifying assumptions a thrust-time history would appear as shown in Fig. 3. The average thrust may be evaluated by

$$F_{avg} = \frac{\int_0^{t_c} F dt}{t_c} = \frac{F}{t_c/(t_D + t_r)} \quad \ldots\ldots [10]$$

Noting that

$$F = (P_3 - P_1)A = AP_1\left(\frac{P_3}{P_1} - 1\right) \quad \ldots\ldots [11]$$

the equations derived earlier may be used to obtain the equation for average thrust as

$$F_{avg} = AP_1 \left\{\frac{1 + \gamma_1 M_1^2}{1 + \gamma_2}\left[1 - \frac{\gamma_2 - 1}{2} M_{2c}\right]^{2\gamma_2/(\gamma_2 - 1)} - 1\right\} \left(\frac{t_D + t_r}{t_c}\right) \quad \ldots [12]$$

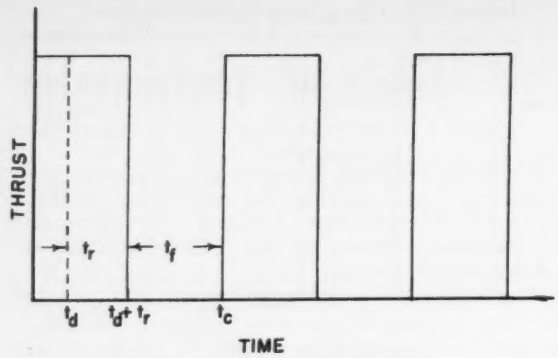

Fig. 3 Idealized thrust-time history

A modified thrust term may be utilized for purposes of calculation, i.e.

$$\frac{F_{avg}}{A}\left(\frac{t_c}{t_D + t_r}\right)$$

Reference (3) shows the results of these calculations for a number of gaseous mixtures. Particular assumptions made in the calculations were that $P_1 = 14.7$ psia, $T_1 = 528$ R, and $\gamma_2 = 1.15$. Experimental values of the velocity (and hence Mach number) of detonation were utilized. The theoretical results for acetylene-oxygen and hydrogen-air mixtures are reproduced in Fig. 4.

The specific impulse may be evaluated from the relation

$$I = \frac{F_{avg}}{w_f + w_0}$$

In those cases where the oxidant is oxygen, the propulsion system is penalized for the rate of oxygen flow as well as the rate of fuel flow. In view of the relations

$$w_f = \frac{w_{f_c}}{t_c} = \frac{\rho_f A L f}{t_c}$$

and

$$w_0 = \frac{w_{0_c}}{t_c} = \frac{\rho_0 A L (1 - f)}{t_c}$$

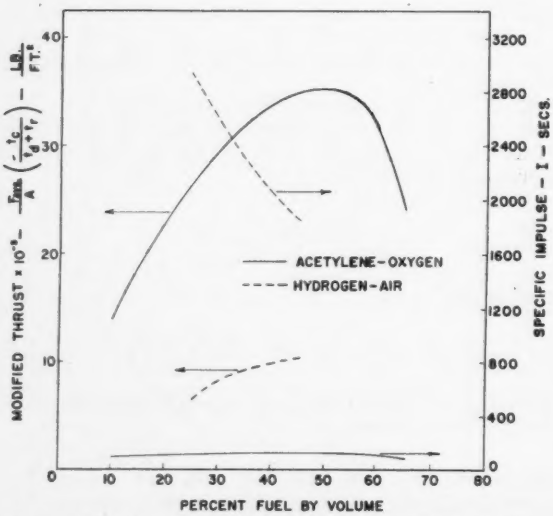

Fig. 4 Theoretical thrust and impulse characteristics of intermittent detonation

the specific impulse may be written

$$I = \frac{P_1\left\{\frac{1 + \gamma_1 M_1^2}{1 + \gamma_2}\left[1 - \frac{\gamma_2 - 1}{2} M_{2c}\right]^{2\gamma_2/(\gamma_2 - 1)} - 1\right\}(t_D + t_r)}{L[\rho_f f + \rho_0(1 - f)]} \quad \ldots\ldots [13]$$

The length L may be eliminated by expressing t_D and t_r in terms of L and the respective velocities so that

$$I = \frac{P_1\left\{\frac{1 + \gamma_1 M_1^2}{1 - \gamma_2}\left[1 - \frac{\gamma_2 - 1}{2} M_{2c}\right]^{2\gamma_2/(\gamma_2 - 1)} - 1\right\}\left\{\frac{1}{V_1} + \frac{\gamma_1 M_1}{\gamma_2 a_1}\frac{(1 + \gamma_2)}{(1 + \gamma_1 M_1^2)}\right\}}{\rho_f f + \rho_0(1 - f)} \quad \ldots\ldots [14]$$

The results of these calculations for the same two gases are also included in Fig. 4.

Measurements on a Single Detonation Wave

The theoretical analysis just discussed involves a number of simplifying assumptions that could prove to be all important to the successful operation of an intermittent detonation engine. In order to isolate some of these parameters it was decided to perform preliminary experiments on a single detonation wave. It was felt that this approach would be more fruitful than a direct attempt at intermittent detonation where the detailed wave processes would be obscured. Accordingly a detonation tube was fabricated and suspended from the ceiling as a pendulum. The particular mixture to be studied was premixed in a stainless steel reservoir and admitted to the detonation tube by means of a detachable line and petcock arrangement. After purging the tube with the mixture, the petcock was closed, the fuel line detached, and the downstream end of the tube sealed with a paper diaphragm. The mixture was ignited by a conventional spark plug or glow plug.

The impulse derived from the ensuing detonation wave was determined experimentally by noting the deflection of the pendulum. Additional information was obtained from a Schaevitz accelerometer which was mounted at the center of the detonation tube. Hence information could be gained as to the variation of thrust with time. The output of the accelerometer was displayed on an oscilloscope and photographed by means of a Polaroid land camera. The experimental arrangement and instrumentation for all of the pendulum measurements are shown in Fig. 5.

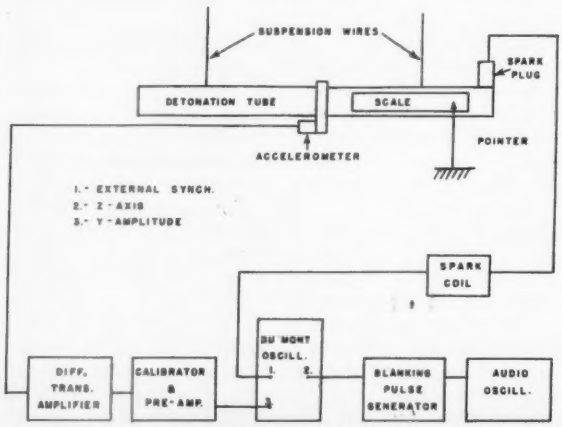

Fig. 5 Instrumentation for pendulum experiments

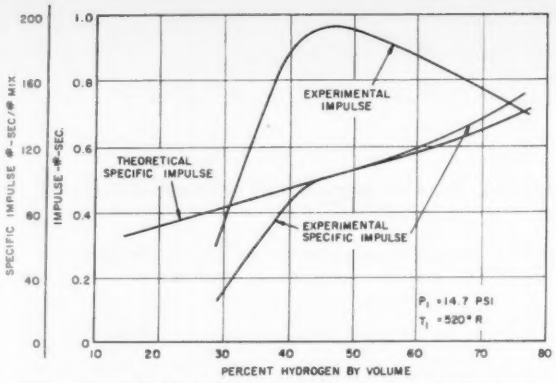

Fig. 6 Impulse derived from hydrogen-oxygen detonations

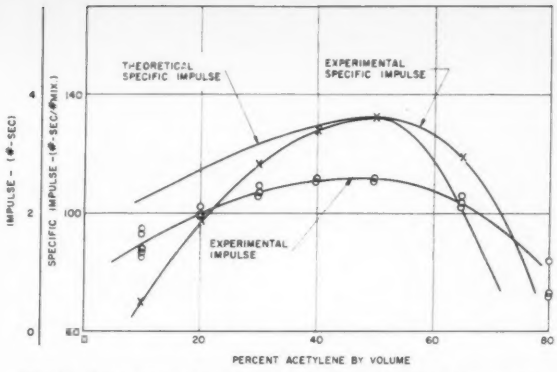

Fig. 7 Impulse derived from acetylene-oxygen detonations

The differential transformer amplifier served as a power supply and amplifier for the accelerometer while the audio oscillator and blanking pulse generator established the time base by blanking out the trace at desired time intervals. A single sweep on the oscilloscope was effected by the discharge of the spark.[6]

Representative runs showing the variation of impulse with volumetric mixture ratio for hydrogen-oxygen and acetylene-oxygen detonations are shown in Figs. 6 and 7, respectively. Comparison with theory was effected by dividing the impulse by the weight of mixture in the detonation tube. The results for hydrogen-oxygen reveal very good agreement between experiment and theory for mixtures richer than about 40 per cent. This mixture ratio corresponds to the dividing line between relatively clean detonations and those where the combustion tends to lag the shock front. This lag increases as the mixture is leaned further. It appears reasonable that the leaner mixtures require greater time to detonate and consequently the impulse is lowered.

It might be noted from the figure that the specific impulse continues to increase beyond the point of maximum impulse. This effect is attributable to the decreasing weight of the mixture with increasing hydrogen, which is sufficient to overbalance the reduction in impulse.

The results for the acetylene-oxygen experiments reveal only fair agreement with theory. It might be noted that the impulse obtained is about three times that realized with hydrogen-oxygen mixtures.

Fig. 8 shows the variation of acceleration (proportional to thrust) with time for a 50 per cent acetylene-oxygen mixture. The simplified theoretical prediction is shown for comparison. In Fig. 7 it can be noted that this mixture gave good agreement between measured and predicted impulse. In view of Fig. 8, this merely implies that the area under the theoretical and experimental curves is the same but obviously the thrust-time history is markedly different. Time equals zero in Fig. 8 represents the time of spark plug energization so that the delay in establishing detonation is evident. Part of this delay, however, is the finite time for the force to be transmitted longitudinally through the tube walls and to the accelerometer.

The rarefaction zone, assumed as a discontinuity for simplicity in the theoretical calculations, is seen to gradually reduce the pressure so that the time of the thrust-producing cycle is materially lengthened. The maximum acceleration (and hence pressure) as indicated by the accelerometer is undoubtedly somewhat lower than that actually experienced because of the finite frequency response of the accelerometer (about 800 cps).

Additional experiments were conducted in the pendulum mounted detonation tube which sought to determine the effect of: (a) Various size orifices and diaphragm materials at the exhaust end, (b) supersonic nozzle at the exhaust end, (c) delay in the initiation of detonation, (d) collision of a detonation wave with a gaseous interface (such as would occur when the tube was not completely filled with the unburned mixture).

For greater detail on any of the pendulum experiments the reader is referred to (5, 9, 10).

Cyclic Detonation Tube

The initial attempt (10) at achieving intermittent detonative combustion was made on a tube of about 1 in. ID and 6 ft in length. Hydrogen and oxygen were injected separately through check valves and impinged on the automotive-type spark plug at the closed end of the tube. Operation of this tube did not prove successful as the first detonation resulted in continuous burning of the ensuing fresh charge. The charging system was altered so that the fresh gases were directed

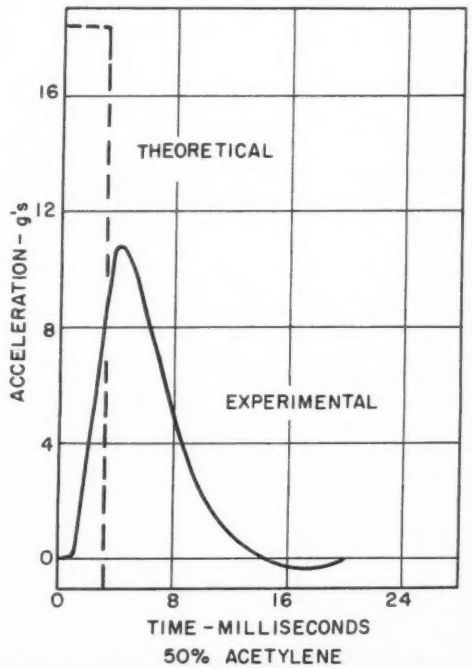

Fig. 8 Detonation tube acceleration vs. time for 50 per cent acetylene-oxygen detonation

[6] The assistance of E. J. Schaefer in resolving the instrumentation difficulties is gratefully acknowledged.

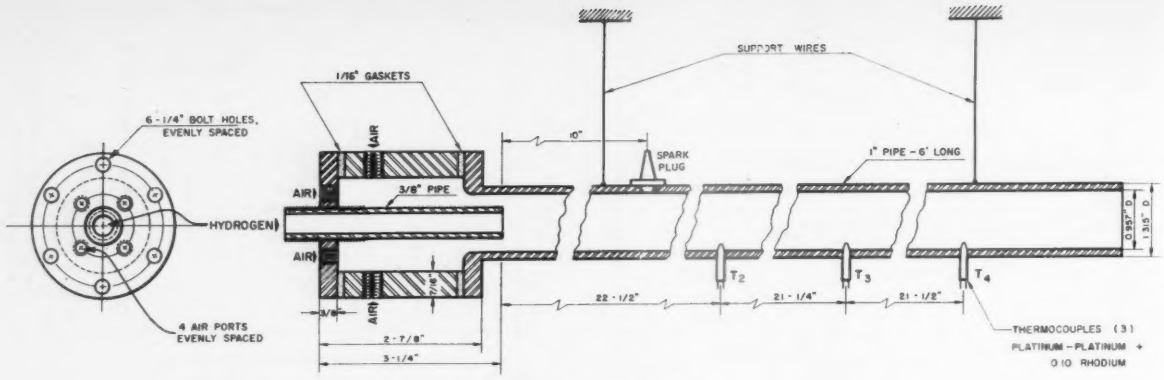

Fig. 9 Cyclic detonation tube

coaxially downstream at a velocity of around 150 fps. The spark plug was located at about 10 tube diameters downstream of the initial mixing plane of the two gases.

Hydrogen-oxygen mixtures were tried on the revised tube and again the same difficulty was experienced. Further tests were made with the spark plug in different locations. The results were the same but it was noted that the tube walls always got hot immediately downstream of the active spark plug. Evidently the initial detonation was sufficient to establish the spark plug or the walls as a flameholder.

Successful cyclic detonative operation of the same tube was achieved in January 1955 by utilizing hydrogen-air mixtures. With the mixture ratio adjusted correctly the tube fired in very sharp, clear, even explosions and estimated frequencies of 35 cps were attained.

This tube was mounted and instrumented so that measurements of thrust, air flow, hydrogen flow and temperature could be made. The tube details are shown in Fig. 9. As shown, hydrogen was introduced in the downstream direction by means of a length of standard $^3/_8$-in. pipe. An air manifold surrounding the hydrogen injector was fed by eight inlet lines and served to admit the air coaxially with the hydrogen. A 0.090-in.-diam orifice was located in the hydrogen line at the inlet to the tube so as to prevent partially gas dynamic coupling between the charging line and the detonation tube. Similarly, a 0.125-in.-diam orifice was placed in each of the air lines. The three thermocouple locations and spark plug location are indicated on the figure. Initial tests were made where the spark plug was located 2 and 5 in. downstream of the initial mixing plane. These positions produced spasmodic firing so the position 10 in. downstream was used in all tests reported. An attempt to detonate the tube with the plug 6 in. from the open end was unsuccessful.

A schematic of the experimental setup and instrumentation is shown in Fig. 10. The compressed air was obtained from two 80 cu ft, high pressure, air-storage vessels. These vessels were ordinarily charged to about 1000 psi by means of two Ingersoll-Rand compressors although the system has a potential of 3000 psi. The air flow was regulated by means of two Grove dome control valves connected in parallel. Bottled nitrogen with a regulator was used to control the dome pressure. The air flow was measured by a 0.284-in.-diam orifice in a 3-in. pipe. The hydrogen flow was controlled by means of a regulator on a commercial gas cylinder. The flow was metered by a 0.106-in.-diam orifice in a 1-in. pipe. During operation of the cyclic detonation tube no unsteadiness was experienced in the air orifice readings so that the average flow rate was obtained. The pressure drop across the hydrogen orifice did oscillate, but not severely. Upstream orifice pressures were read on a Bourdon-type pressure gage and the orifice pressure drops were read on mercury manometers.

An automotive-type spark plug was used with the conventional distributor and spark coil arrangement. The distributor was driven by a variable-speed brush-controlled motor so that cycling frequency could be varied as desired.

Three platinum-platinum +0.10 rhodium thermocouples were mounted along the tube as shown in Fig. 10. The junctions were arranged so that a gas temperature near the tube wall would be obtained. The response time of the thermocouples restricts the measurements to average values although qualitative cyclic changes were discernible. The outputs of the thermocouples were fed to galvanometer movements of a 50-channel Consolidated Recording Oscillograph, Type 5-119. The data were recorded photographically and then developed on the Consolidated Oscillogram Processor, Type 23-109.

The measurement of thrust was achieved by mounting the

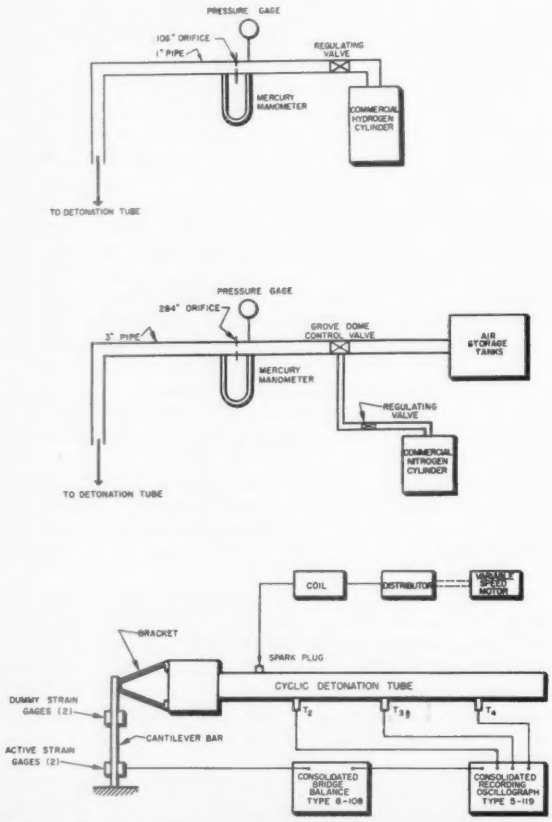

Fig. 10 Experimental arrangement for intermittent detonation tests

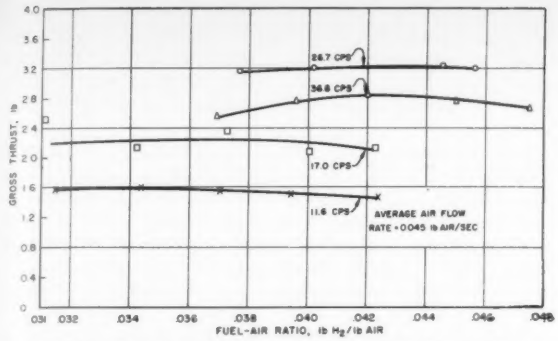

Fig. 11 Thrust vs. fuel-air ratio for various frequencies

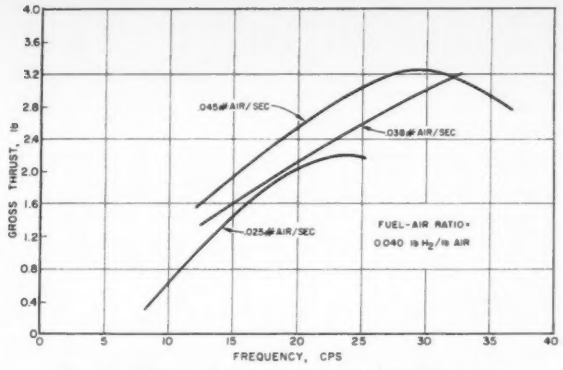

Fig. 12 Thrust vs. frequency for various flow rates

thrust end of the tube to the free end of a cantilever beam. Two active SR-4 strain gages, one in tension and one in compression were mounted near the supported end of the beam so that the thrust could be calibrated in terms of the bending stresses. Two dummy strain gages of the same type completed the bridge circuit. A Consolidated Bridge Balance, Type 8–108, was used as the control link between the strain gages and oscillograph. The thrust readings were restricted to average values. Although good frequency response was desired, it had to be sacrificed in order to get sufficient strain-gage output.[7]

The experimental procedure in making test runs was to adjust the air for the desired flow rate, adjust the motor speed to the desired frequency, regulate the hydrogen flow, close the spark circuit and then record the data. Because of the rapid use of hydrogen it was often necessary to record data while the cyclic detonation tube and strain-gage mount were oscillating at relatively high amplitudes. In those cases it was necessary to take the average reading.

Results of Intermittent Detonation Experiments

The thrust data to be presented for the tests on intermittent detonative combustion are actually gross thrust and have not been corrected for the thrust increment due to the momentum of the fresh gases. For the most part this introduces little error.

Fig. 11 represents the variation of thrust with fuel-air ratio for a number of operating frequencies and at one air flow rate. During the runs, too lean or too rich a mixture caused a continuous burning rather than intermittent detonation. Some of the scatter in the experimental points may be attributed to a slight change in cycling frequency during the course of the run.

Fig. 12 shows the variation of thrust with cycling frequency for a fuel-air ratio of 0.040 and for three different air flow rates. This information is taken from the data in Fig. 11 and other similar data. As would be expected, the influence of frequency is all-important. It is seen that the curves for the lowest and highest air flows reach a maximum and then fall off. This is not surprising in that high cycling frequencies imply that the fresh charge does not fill the entire length of the tube. Consequently, there will be a collision of the detonation wave with the burned products of the previous cycle, which will probably result in a mild rarefaction reflected upstream and a shock transmitted downstream. This will lead to some loss in thrust but, over a certain range, should result in greater fuel economy. This aspect has been treated mathematically in (5).

The intermediate air-flow run in Fig. 12 indicates no maximum in the range shown. Additional data had been obtained on cyclic frequencies to 51.7 cps at this air flow rate but the thrust readings were doubtful and hence were discarded.

The results shown in Fig. 12 may also be plotted to show the variation of specific impulse with cycling frequency for this same fuel-air ratio of 0.040. This plot is shown in Fig. 13 and it is seen that quite high specific impulse is realized for the higher frequency runs. Comparison of Figs. 12 and 13 reveals that the thrust increases with higher flow rates while the specific impulse decreases.

Fig. 14 is a plot of the experimental temperature T_3 (see Fig. 9) as a function of fuel-air ratio and for various frequencies. The other temperatures were somewhat lower and lower air flows produced slightly lower temperatures. In most cases the oscillograph traces indicated that the temperature had stabilized and it is somewhat surprising that the level is so low. Different fuels could, of course, appreciably increase this level. The fuel-air ratios are richer than stoichiometric which explains the decreasing temperature with fuel-air ratio.

Prior to the time when the detonation tube was instrumented, a test was run wherein the spark plug was replaced by a glow plug so that ignition was obtained from a hot wire. After the initial energization of the wire, the tube detonated intermittently and evenly at some moderate frequency without further energization of the wire. The fuel supply had to be cut off in order to cease firing. This aspect may be of some utility in an actual engine.

In order to prove that the detonation tube was actually detonating, a Control Engineering Corporation, Model 2DC, Engine Pressure Indicator was procured locally on a loan basis and mounted 16 in. from the open end of the tube. The response of this pickup is quoted by the manufacturer as

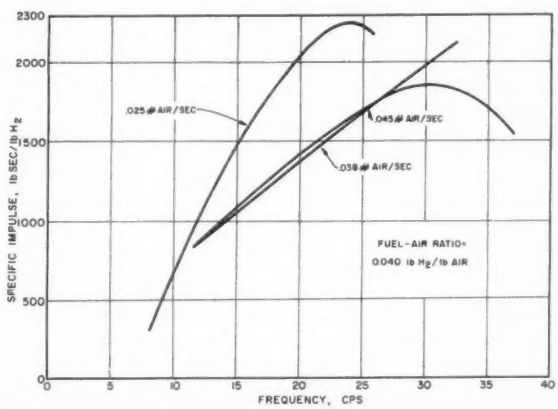

Fig. 13 Specific impulse vs. frequency for various flow rates

[7] Appreciation is extended to D. R. Glass for his aid in the instrumentation aspects.

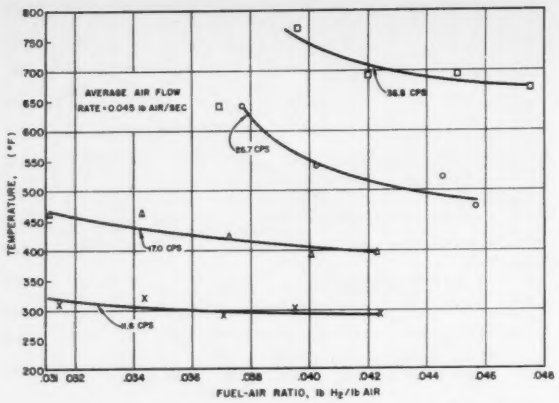

Fig. 14 Temperature (T_3) vs. fuel-air ratio for various frequencies

linear to 20,000 cps. The output of the pickup with its associated bridge balance was connected to the vertical input of a Textronix oscilloscope, Type 513-D. With the detonation tube in operation at moderate frequencies and the horizontal sweep of the scope set at one millisecond per centimeter, the initial pressure indication for each cycle appeared as a perfect discontinuity. This evidence, along with the mixture ratios over which the tube operated intermittently, the type of noise generated, and the close agreement with theory, leaves little doubt that the tube was actually detonating.

Unfortunately, the above pressure pickup yielded insufficient output for quantitative work.

Discussion

One of the primary motives of this initial work on intermittent detonation has been to establish an order of magnitude on the discrepancy between experiment and theory. With such information it is possible to extrapolate to some future potential on the basis of a merit factor that would evolve in development work. The experimental work reported here has been concerned with only hydrogen-air mixtures. It appears reasonable that other gaseous mixtures could be utilized with about the same deviations from theory. To be sure, certain mixtures may involve difficulty, such as a tendency to detonate or burn prematurely, and it may be a practical but solvable problem to overcome it.

The results of the experiments with hydrogen-air are compared with theory in Fig. 15. Only one frequency is shown for each of the three air flow rates. The close agreement for the lower mass flow rates is encouraging, but rather surprising in view of the simplifying assumptions made in the analysis. The same information is plotted in terms of specific thrust (pounds thrust per square foot of tube area) in Fig. 16. As predicted, hydrogen-air mixtures yield low values of specific thrust. It may be noted that the thrust increases with higher mass flow whereas the specific impulse drops off. The theoretical predictions of thrust are expressed in the form of a modified thrust term which is the average thrust per unit area multiplied by a time parameter $t_c/(t_D + t_r)$. Comparing the experimental value of specific thrust obtained for a fuel-air ratio of 0.043 (38.2 per cent by volume) and an air flow rate of 0.045 lb/sec (Fig. 16) with the theoretical value from Fig. 4, the time parameter indicated is 15. This agrees quite closely to the calculated value based on the experimental 26.7 cps although admittedly the experimental arrangement was slightly different from that used for the theoretical calculations.

The successful operating range for intermittent detonation with hydrogen-air mixtures was practically all in the rich mixture range. This agrees with known detonation limits (2) although some of this effect may be attributed to incomplete mixing at this spark plug where the mixture would be somewhat lean. Consequently, a different spark plug location could conceivably move the operating range toward leaner mixtures.

Hoffman (4) has indicated the importance of spark plug location in reference to tube length and diffuser length. This aspect has not been investigated in the present program but is a logical extension. It is believed that material gains over present performance could be achieved by such investigations. Also, there are undoubtedly many improvements in the charging system that could be effected as well as changes in the tube geometry.

Hoffman operated successfully with acetylene-oxygen mixtures by using water-vapor additions to prohibit premature burning. He failed to give tube dimensions so that the values of specific thrust attained are not known. However, if we assume the value of the time parameter as 15 (as indicated by the hydrogen-air tests), the theoretical calculations would predict a specific thrust of 2400 lb/ft². But this is based on very preliminary studies and it is believed that considerable improvement could be realized with further research and development.

Conclusions

A simplified theoretical analysis of a reaction device operating on intermittent detonation waves predicts high thrust levels and low specific impulse for most gaseous mixtures. However, in the case of hydrogen-air mixtures the reverse characteristics are indicated. Preliminary experimental results on a cyclic detonation tube operating on hydrogen-air mixtures show good agreement with theory and a specific impulse of over 2100 sec has been obtained. Conceivably, other mixtures could be utilized wherein the performance would be toward high thrust levels but at the expense of fuel economy.

The experiments reported were confined to a single tube with a single source of ignition. It is doubtful that an intermittent detonation engine could operate efficiently with a single tube and single source of ignition, as the diameter

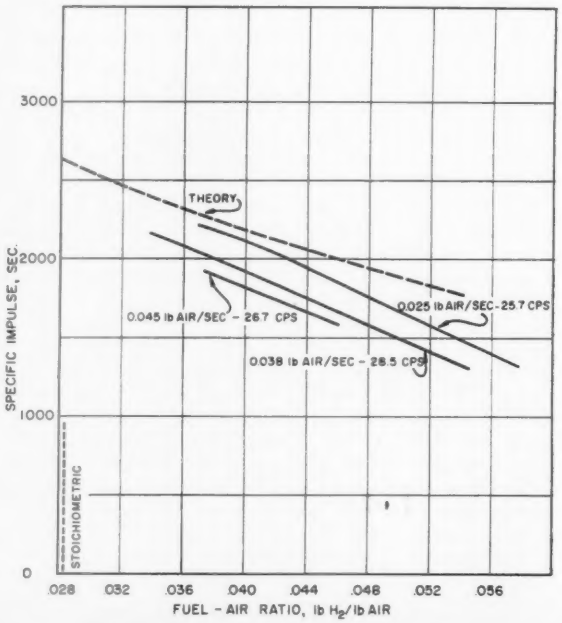
THEORY
0.045 lb AIR/SEC - 26.7 CPS
0.025 lb AIR/SEC-25.7 CPS
0.038 lb AIR/SEC - 28.5 CPS
STOICHIOMETRIC
SPECIFIC IMPULSE, SEC.
FUEL - AIR RATIO, lb H2/lb AIR

Fig. 15 Specific impulse vs. fuel-air ratio

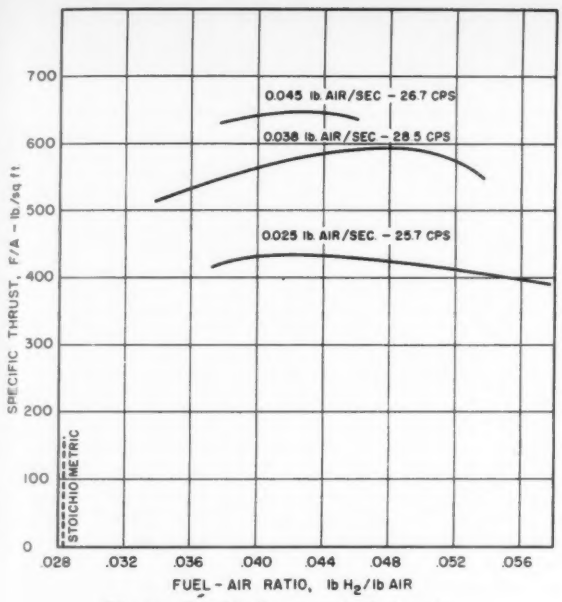

Fig. 16 Specific thrust vs. fuel-air ratio

required for the thrust demands would involve prohibitive lengths for the development of detonation. However, a bank of small tubes could be mounted very compactly so that the frontal area would be quite small compared to other reaction devices of the same thrust level. A rotating valve may be ideally suited to such an arrangement.

It appears that an intermittent detonation engine would offer many advantages. Among these advantages are extreme mechanical simplicity, static thrust capabilities as well as efficient operation at supersonic velocities and high thrust levels or high fuel economy, depending on the fuel utilized.

The results to date would seem to warrant further exploration into the intermittent detonation cycle engine. Those areas of research deemed to be the most fruitful are those involving valving, charging arrangement, tube length, spark plug position and diffuser. Consideration should also be given to "tuned" frequencies where ignition is effected through reflected shocks or detonations or by hot wire.

References

1 Morrison, R. B., "A Shock Tube Investigation of Detonative Combustion," Report UMM-97, University of Michigan, Engineering Research Institute Project M898, Jan. 1952.

2 Nicholls, J. A., Morrison, R. B., Reid, F. A., and Ong, R., "Final Report on Detonative Combustion," University of Michigan, Engineering Research Institute Project M898, Aug. 1953.

3 Morrison, R. B., Nicholls, J. A., and Ong, R., "Preliminary Calculations on the Thrust and Impulse Characteristics of Intermittent Detonation," University of Michigan, Engineering Research Institute, unpublished.

4 Hoffman, H., "Reaction Propulsion by Intermittent Detonative Combustion," Ministry of Supply, Volkenrode translation.

5 Nicholls, J. A., Wilkinson, H. R., Morrison, R. B., and Ong, R., "Intermittent Detonation as a Thrust-Producing Mechanism," University of Michigan, Engineering Research Institute Project 2172, July 1954.

6 Bitondo, D., and Bollay, W., "Preliminary Performance Analysis of the Pulse-Detonation-Jet Engine System," Aerophysics Development Corp., Report ADC-102-1, April 1952.

7 Bitondo, D., Kendrick, J. B., and Bollay, W., "Preliminary Report on the Application of the Pulse-Det-Jet Engine to Helicopter Rotor Propulsion." Aerophysics Development Corp., Report ADC-102-3, August 1952.

8 Rutowski, J., and Nicholls, J. A., "Considerations for the Attainment of a Standing Detonation Wave," University of Michigan, Engineering Research Institute Project 2284, presented at the Gas Dynamics Symposium, Northwestern University, Aug. 22–24, 1955.

9 Nicholls, J. A., Wilkinson, H. R., and Morrison, R. B., "Intermittent Detonation as a Thrust-Producing Mechanism," University of Michigan, Engineering Research Institute Project 2172, Jan. 1954.

10 Nicholls, J. A., Wilkinson, H. R., and Morrison, R. B., "Intermittent Detonation as a Thrust-Producing Mechanism," University of Michigan, Engineering Research Institute Project 2318, Jan. 1955.

An Analysis of Heating Problems in Supersonic Ramjet Tailpipes

(Continued from page 521)

without ceramic coating, a numerical stepwise transient method was used. It was assumed that instantaneously

Q (gas to metal) = (rate of heat storage in metal per unit time per unit area) + Q (metal to environs)

If primes denote values at the end of a finite time interval, and absence of primes denotes values at the beginning of the interval, this is expressed by the difference equation

$$(h_{rg}(T_g - T_m) + h_{cg}(T_{tg} - T_m)] = [(cdx)_m(T_m' - T_m)/(t' - t)] + [h_{ro}(T_m - T_o) + h_{co}(T_m - T_{to})]$$

If one writes $Y = (cdx)_m/(t' - t)$ and solves for T_m', one obtains

$$T_m' = (1/Y)(h_{rg}T_g + h_{cg}T_{tg} + h_{ro}T_o + h_{co}T_{to}) - (T_m/Y)(h_{rg} + h_{cg} + h_{ro} + h_{co} - Y)$$

If at $t = 0$ the initial value of T_m is given, and all the other temperatures and coefficients are known (e.g., at the start of a ramjet launch transient), then the equation above allows the metal temperature T_m' at end of time interval $(t' - t)$ to be found. This may be repeated for the succeeding time intervals up to the end of the transient. For the cases analyzed, the intervals were all kept equal to 1 sec which insured sufficient accuracy. Digital computing machines were used to calculate thin wall transients by this method.

2. For metal walls with temperature gradients, and for all walls with internal ceramic coating, the graphical and numerical transient conduction methods due to Schmidt and Dusinberre, as presented in (5, p. 43 et seq.), were used, with time intervals of close to 1 sec.

References

1 Thomas, A. N., "How to Match Ramjet Inlets and Performance," *Aviation Age*, vol. 25, Feb. 1956, p. 24.

2 Marsh, B. W., and Sears, G. A., "Introduction to the Analysis of Supersonic Ramjet Power Plants," JET PROPULSION, vol. 24, no. 3, May-June 1954, pp. 155–161.

3 "Equations, Tables, and Charts for Compressible Flow," Ames Laboratory Research Staff, NACA Report 1135, 1953.

4 "Manual of the ICAO Standard Atmosphere—Calculations by the NACA," NACA TN 3182, May 1954.

5 McAdams, W. H., "Heat Transmission," 3rd edit., McGraw-Hill, New York, 1954.

6 Eber, G. R., "Experimental Research on Friction Temperature and Heat Transfer for Simple Bodies at Supersonic Velocities," Microfilm 66/57 (Peenemunde).

7 Hall, N. A., and Mulready, R. C., "Ideal Temperature Rise from Constant Pressure Combustion of Hydrocarbon Fuels," SAE Paper presented at New York, April 1948. (Previously published as United Aircraft Corp. Meteor Report UAC-9, July 1947.)

8 Levy, A. V., "Evaluation of Some New Materials for Missile and Powerplant Applications," Paper presented at ARS Meeting, Chicago, Nov. 1955.

Technical Notes

Impulse Expressions for Rocket Systems Containing a Solid Phase

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Many procedures have been used for calculating the specific impulse of rocket motors whose combustion products contain solids. Since for the pure gaseous system the expression (Reference 1)

$$I_{sp} = \sqrt{\frac{2}{g}\frac{\gamma}{\gamma-1}\frac{R}{M.W.}T_c\left[1-\left(\frac{p_e}{p_c}\right)^{\gamma/(\gamma-1)}\right]}$$

has seen general use, this note attempts to show that the specific impulse of a gas-solid system can be represented by similar expressions in which the ratio of the specific heats and the average molecular weight are redefined.

Nomenclature

c = specific heat of solid; $c_{p_s} = c_{v_s} = c_s$
C_p = total specific heat at constant pressure, cal/°C
c_p = specific heat at constant pressure, cal/gm °C
c_v = specific heat at constant volume
g = gravitational constant
H = heat content
I_{sp} = specific impulse
m = mass flow rate
$M.W.$ = molecular weight;

$$\overline{M.W.} = \frac{n_g M.W._g + n_s M.W._s}{n_g}$$

for multicomponent systems

$$\overline{M.W.} = \frac{\Sigma_i (n_g M.W._g)_i + \Sigma_j (n_s M.W._s)_j}{\Sigma_i (n_g)_i}$$

n = number of moles
P = pressure
R = universal gas constant
T = temperature
u = velocity
w = weight fraction of solids
γ = ratio of specific heats
η = an analogous γ

$$\eta = \frac{(1-w)c_{p_g} + w c_{p_s}}{(1-w)c_{v_g} + w c_{v_s}}$$

for multicomponent systems

$$\eta = \frac{\Sigma_i(\omega_g C_{p_g})_i + \Sigma_j(\omega_j C_s)_j}{\Sigma_i(\omega_g C_{v_g})_i + \Sigma_j(\omega_j C_s)_j}$$

ω = weight fraction of individual component in multicomponent system

Subscripts

c = chamber
e = nozzle exit
g = gas
i = index referring to gaseous system
j = index referring to solid components
s = solid

THERE are many procedures by which one may calculate the theoretical performance of a rocket motor when it is known a condensed phase is formed in the chamber. A review of these procedures has recently been given by Altman and Carter (2).[2] In determining the theoretical performance of a rocket motor in which a solid component is formed in the chamber, one may accurately calculate the adiabatic temperature. It is in the use of the proper conditions in the expansion process where particular considerations must be given to the average molecular weight and "ratio of specific heats of the solid-gas mixture," the temperature history of the solid component in the expansion process, etc.

It has become the accepted procedure to refer to the analytical calculation which assumes complete kinetic and thermal equilibrium between the solid particles and the flowing product gases as the ideal theoretical performance calculation. This can be considered one limiting case. Others, following the analysis given in (2) are: (a) Kinetic equilibrium with the particles thermally insulated, (b) thermal equilibrium with zero particle speed, and (c) complete insulation with the particles remaining at the chamber temperatures and having zero velocity.

Altman and Carter (2) give for the so-called ideal case (case 1) ($u_s = u_g$, $T_s = T_g$)

$$dH = (C_{p_g} + C_{p_s})dT = V\,dP \quad \ldots\ldots [1]$$

If the gas containing the solid is assumed to be perfect, the equation of state can be written as

$$PV = n_g RT \quad \ldots\ldots [2]$$

Assuming constant specific heat, Equations [1 and 2] are combined to give

$$\frac{T_e}{T_c} = \left(\frac{P_e}{P_c}\right)^{n_g R/(C_{p_g}+C_{p_s})} \quad \ldots\ldots [3]$$

Integrating Equation [1] between the chamber and exit temperatures gives

$$\Delta H_{T_c}^{T_e} = (C_{p_g} + C_s)(T_c - T_e) = \frac{1}{2}mu^2 \quad \ldots\ldots [4]$$

Factoring T_e in Equation [4] and substituting Equation [3] for T_e/T_c, one obtains an expression for the specific impulse

$$I_{sp} = \frac{u}{g} = \frac{1}{g}\sqrt{\frac{2(C_{p_g}+C_s)}{m}T_c\left[1-\left(\frac{P_e}{P_c}\right)^{n_g R/(C_{p_g}+C_s)}\right]} \quad \ldots [5]$$

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[2] Numbers in parentheses indicate References at end of paper.

EDITOR'S NOTE: This section of JET PROPULSION is open to short manuscripts describing new developments or offering comments on papers previously published. Such manuscripts are published without editorial review, usually within two months of the date of receipt. Requirements as to style are the same as for regular contributions (see masthead page of this issue).

This expression may be rewritten as described below. Now

$$C_{pg} = n_g M.W._g\, c_{pg}$$

$$C_s = n_s M.W._s c_s$$

and

$$m = n_g M.W._g + n_s M.W._s$$

Thus $(C_{pg} + C_s)/m$ becomes $g[(1 - w)\, c_{pg} + wc_s]$ where w is the weight fraction of solids. Now let us define a term η, which is the analog[3] of the pure gas γ, as follows[4]

$$\eta = \frac{(1 - w)c_{p_g} + wc_s}{(1 - w)c_{v_g} + wc_s} \quad \ldots\ldots [6]$$

It is readily shown

$$g[(1 - w)c_{p_g} + wc_s] = \frac{\eta}{\eta - 1}\,\frac{R}{\overline{M.W.}} \quad \ldots\ldots [7]$$

where R is the universal gas constant and $\overline{M.W.}$ is the average molecular weight of the gas containing solids and is equal to

$$\overline{M.W.} = \frac{n_g M.W._g + n_s\, M.W._s}{n_g} \quad \ldots\ldots [8]$$

Similarly it can be shown that

$$\frac{n_g R}{C_{pg} + C_s} = \frac{\eta - 1}{\eta} \quad \ldots\ldots [9]$$

Then the expression for specific impulse can be written

$$I_{sp} = \sqrt{\frac{2}{g}\left(\frac{\eta}{\eta - 1}\right)\frac{R}{\overline{M.W.}}\, T_c\left[1 - \left(\frac{p_e}{p_c}\right)^{(\eta-1)/\eta}\right]} \quad [10]$$

which is similar to the expression generally used to calculate the specific impulse when only gases are present except that the ratio of specific heats and the average molecular weight have been redefined.[5]

For case 2, $u_s = u_g$ but $T_s = T_c$, the same equation for the specific impulse holds except the term C_s is now omitted whenever it appears. This is readily understandable without the necessity of a complete derivation, since it simply states that there is no energy given up by the solid to the gas stream. The expression for impulse then is

$$I_{sp} = \frac{1}{g}\sqrt{\frac{2C_{pg}}{m}\, T_c\left[1 - \left(\frac{p_e}{p_c}\right)^{n_g R/C_{pg}}\right]} \quad \ldots\ldots [11]$$

which can be shown to be

$$I_{sp} = \sqrt{\frac{2}{g}\left(\frac{\gamma}{\gamma - 1}\right)\frac{R}{\overline{M.W.}}\, T_c\left[1 - \left(\frac{p_e}{p_c}\right)^{(\gamma-1)/\gamma}\right]} \quad [12]$$

In the third case $u_s = 0$, $T_s = T_g$—all the available energy is translated into kinetic energy of the gas, so that the expression for the I_{sp} becomes

$$I_{sp} = \frac{(1 - w)u_g}{g} = \frac{(1 - w)}{g}\sqrt{\frac{2(C_{pg} + C_s)(T_c - T_e)}{m(1 - w)}} \quad [13]$$

which can be rewritten with the newly defined terms as

$$I_{sp} = \sqrt{\frac{2(1 - w)}{g}\left(\frac{\eta}{\eta - 1}\right)\frac{R}{\overline{M.W.}}\, T_c\left[1 - \left(\frac{p_e}{p_c}\right)^{(\eta-1)/\eta}\right]} \quad \ldots\ldots [14]$$

[3] It is the author's recollection that this term was first suggested by H. Seifert.

[4] In Equation [6] w may be replaced by the mol fraction of solids, providing molar specific heats are used in the equation.

[5] Dillon and Line (3) have recently treated a form of this case. This result can be shown to be the same as Equation [10] except that they employ $M.W._g/(1 - w)$ for $\overline{M.W.}$. The two expressions are equivalent.

This case approximates the condition in which the solid particles have extremely slow velocities.

In case 4, $u_s = 0$, $I_s = T_c$, and as explained previously, one need only omit the C_s term, this time in Equation [13]. The desired expression for this case becomes

$$I_{sp} = \sqrt{\frac{2(1 - w)}{g}\,\frac{\gamma}{\gamma - 1}\,\frac{R}{\overline{M.W.}}\, T_c\left[1 - \left(\frac{p_e}{p_c}\right)^{\gamma/(\gamma-1)}\right]} \quad \ldots [15]$$

For the general system containing more than one gaseous component and more than one solid material, the explicit relationships in Equations [10, 12, 14 and 15] hold, except that the definitions of η and $\overline{M.W.}$ now become

$$\eta = \frac{\Sigma_i(\omega_g c_{pg})_i + \Sigma_j(\omega_s c_s)_j}{\Sigma_i(\omega_g c_{vg})_i + \Sigma_j(\omega_s c_s)_j} \quad \ldots\ldots [16]$$

$$\overline{M.W.} = \frac{\Sigma_i(n_g M.W._g)_i + \Sigma_j(n_s M.W._s)_j}{\Sigma_i(n_g)_i} \quad \ldots\ldots [17]$$

where ω is the weight fraction of the various species.[6] w in Equations [14 and 15] thus becomes $\Sigma_j\,(\omega_s)_j$; γ in Equations [12 and 15] is then the average γ of the gaseous components.

References

1 Sutton, George P., "Rocket Propulsion Elements," 2nd edit., Wiley, New York, 1956, p. 94.

2 Altman, D., and Curtis, J. M., "Combustion Processes," Sect. C., vol. II, "High Speed Aerodynamics and Jet Propulsion," Princeton University Press, 1956.

3 Dillon, P. L. P., and Line, L. E., Jr., "Heat Transfer Between Solid Particles and Gas in a Rocket Nozzle," Jet Propulsion, vol. 26, Dec. 1956, pp. 1091–1097.

[6] ω may be replaced by the mol fraction of the component providing molar specific heats are used in the expression.

A High Temperature Combination Sonic Aspirated Thermocouple and Total Pressure Probe

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A SONIC-aspirated platinum rhodium-platinum thermocouple was built to extend the range of the chromel-alumel types reported in (1, 2)[2] and to be used in a survey apparatus for combustor research (3). The advantage of this type of thermocouple probe is that it is sensibly free of radiation and conduction errors, and the total temperature of the gas is obtained by applying a constant correction factor for recovery.

The present design incorporates a removable insert, with the thermocouple and nozzle as an integral unit of the insert. This feature fixes the position of the junction in the throat of the nozzle and therefore has an advantage over previous designs in which the nozzle was attached to the main body and differential thermal expansion caused uncertainties in relative junction-to-nozzle throat positioning. The insert is enclosed in a main assembly consisting of a $^3/_8$-in. OD, water-cooled, Inconel supporting tube with a platinum-rhodium tube at the sensing end. The head also contains a total-pressure tube to take simultaneous pressure readings. Details of the sensing end of the probe are shown in Fig. 1.

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[2] Numbers in parentheses indicate References at end of paper.

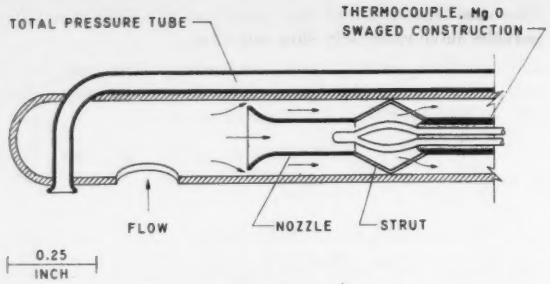

Fig. 1 Sensing end of the probe

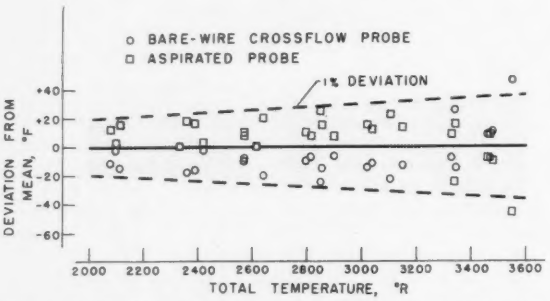

Fig. 2 Comparison of bare-wire cross flow and aspirated water-cooled high temperature probes at static pressure of 1 atm and Mach numbers of 0.4 to 0.6

The probe was tested in a high temperature tunnel, described in (4), through a temperature range from 2100 to 3550 R, a free stream Mach number range of 0.4 to 0.6, and at a static pressure of 1 atm. A platinum rhodium-platinum, bare-wire, cross-flow probe was used as a comparison instrument. The tests were performed by moving each probe, in turn, to the same location in the test section while tunnel conditions were held constant.

Total temperature T_t for the bare-wire, cross-flow probe was obtained by applying recovery, radiation and conduction corrections to the indicated temperature T_{ind} as reported in (5). The total temperature of the aspirated probe was obtained by applying a constant recovery correction of $1^1/_2$ per cent, where $T_t = T_{ind} \times 1.015$. This correction was obtained from a calibration at room temperature.

The results of the high temperature tests are shown in Fig. 2, which is a plot of the deviation from the mean temperature as measured by both pyrometers throughout the temperature range. The agreement is in a band whose limits are on the order of 1 per cent and whose probable error is 0.5 per cent.

References

1 Lalos, G. T., "Sonic Pyrometers for Measuring Gas Temperature," N.B.S. Ninth Quarterly Report of Progress on the Development of Thermocouples for Gas Turbines, July-Sept. 1950.

2 Glawe, G. E., Simmons, F. S., and Stickney, T. M., "Radiation and Recovery Corrections and Time Constants of Several Chromium-Alumel Thermocouple Probes in High Temperature, High Velocity Gas Streams," NACA TN 3766, Oct. 1956.

3 Friedman, R., and Carlson, E. R., "A Polar-Coordinate Survey Method for Determining Jet-Engine Combustion-Chamber Performance," NACA TN 3566, Sept. 1955.

4 Glawe, G. E., and Shepard, C. E., "Some Effects of Exposure to Exhaust-Gas Streams on Emmittance and Thermoelectric Power of Bare-Wire Platinum Rhodium-Platinum Thermocouples," NACA TN 3253, Aug. 1954.

5 Scadron, M. D., and Warshawsky, I., "Experimenal Determinatio.n of Time Constants and Nusselt Numbers for Bare-Wire Thermocouples in High-Velocity Air Streams and Analytic Approximation of Conduction and Radiation Errors," NACA TN 2599, Jan. 1952.

On Excess Enthalpy, Flame Extinction and Minimum Ignition Energies[1]

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Excess Enthalpy of Ozone Decomposition Flames

USING Hirschfelder's numerical solution for the ozone decomposition flame (1),[4] the total excess enthalpy per gram of mixture has been calculated as a function of temperature for a mixture containing 75 per cent oxygen and 25 per cent ozone and an assumed Lewis number Le of 0.94.

The thermal (Δh_T), chemical (Δh_{ch}), and total enthalpies $\Delta h = \Delta h_T + \Delta h_{ch}$ per gram of mixture are plotted as a function of temperature in Fig. 1. Reference to Fig. 1 shows that Δh is everywhere positive but small because the chemical and thermal enthalpy changes nearly cancel for Le close to unity.

Lewis and von Elbe (2) have defined the excess enthalpy as

$$\Delta h_{Le} = \frac{\lambda}{m}\frac{dT}{dx} \quad \ldots\ldots\ldots\ldots\ldots\ldots [1]$$

where λ is the thermal conductivity and m equals the mass flow rate per unit area. The quantity Δh_{Le} is also shown in Fig. 1 and is seen to attain a maximum value nearly ten times

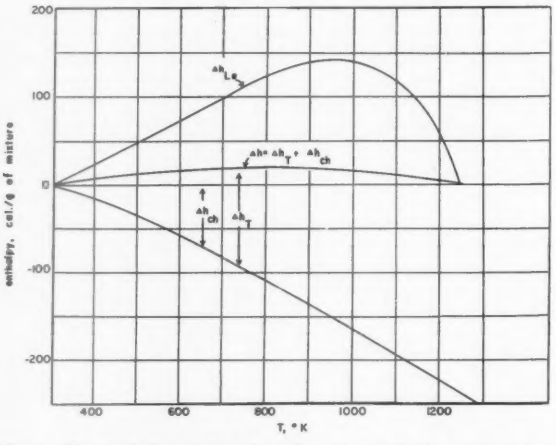

Fig. 1 The enthalpy terms Δh_T, Δh_{ch}, Δh_{Le} and Δh as a function of temperature for the ozone decomposition flame

as large as Δh. Also Δh_{Le} is linear with T and equal to Δh_T in the colder parts of the flame, because here reaction proceeds so slowly that the change in $\bar{c}_p T$ is produced largely by heat conduction. In the hotter parts of the flame, chemical reactions occur rapidly and the change in $\bar{c}_p T$ is now produced mostly by chemical heat release.

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[1] Supported by the Office of Ordnance Research, U. S. Army, under Contract DA-04-495-Ord-446. Further details concerning the work described in this paper may be found in Technical Report 17, Contract DA-04-495-Ord-446, California Institute of Technology, Pasadena, 1957.

[2] Associate Professor of Jet Propulsion. Mem. ARS.

[3] National Science Foundation Predoctoral Fellow. Mem. ARS.

In calculating minimum ignition energies, it is customary to consider the excess enthalpy h_a per unit area of flame front referred to the unburnt gas of density ρ_u, viz.

$$h_a = \rho_u \int_{-\infty}^{\infty} \Delta h \, dx \quad \ldots\ldots [2]$$

If diffusion is neglected in comparison with heat conduction, then h_a is replaced by

$$h_{Le} = \rho_u \int_{-\infty}^{\infty} \Delta h_{Le} \, dx = \frac{\bar{\lambda}}{Su} (T_f - T_0) \quad \ldots\ldots [3]$$

where T_f is the adiabatic flame temperature, Su equals the laminar burning velocity, and the bar indicates that a suitable average has been used for the entire flame width. Lewis' estimate of the minimum ignition energy, $h_{\min}$, is

$$h_{\min} = \pi d_q^2 h_{Le} \quad \ldots\ldots [4]$$

where d_q is the quenching distance. Performing an approximate integration on our graphs we find that, for the ozone decomposition flame, h_{Le} is larger than h_a by about a factor of 5.

In view of this large discrepancy it therefore appears likely that the demonstrated empirical utility of Equation [4] reflects the fact that enthalpy changes produced by heat conduction, rather than total enthalpy changes, are of dominant importance in ignition processes. This last statement is in accord with the conclusions reached by J. W. Linnett (3) after a critical examination of the arguments in favor of the excess enthalpy concept advanced by Lewis and von Elbe (2) and by Burgoyne and Weinberg (4, 5, 6), and after a critical examination of the relevant objections raised by Spalding (7).

Flame Extinction

Equation [4], as well as Spalding's critical size for a burnt gas slab which will just support combustion (8), are consistent with the following basic postulate: Thermal ignition will occur if the rate of energy transport per unit area by thermal conduction equals the rate of enthalpy change per unit area for a steadily propagating flame when energy transport by diffusion is neglected.

For one-dimensional, steady, inviscid, constant-pressure flow problems without external forces, the equation for conservation of energy reduces to

$$m \Delta h = \Delta q \quad \ldots\ldots [5]$$

where Δh denotes the change in the specific enthalpy for the mixture with constant mass flow rate m to which the total heat transfer by conduction and diffusion is Δq. The preceding relation may be applied to a stationary combustible mixture through which a laminar flame is propagated. In this case we identify $v = m/\rho$ with the mass-weighted average velocity of the burning gas relative to the flame front.

Consider a slab of burnt gas of finite width at the adiabatic flame temperature T_f in contact with a semi-infinite slab of combustible gas at the temperature T_0. According to our basic postulate, we may use for Δq in Equation [5] a suitable average value for $\lambda(dT/dx)$ which we approximate by $\bar{\lambda}(T_f - T_0)/\delta$ where δ is the effective width of the laminar flame front which is propagated at the constant speed Su. Equation [5] now becomes

$$\rho_u \delta \Delta h = \frac{\bar{\lambda}}{Su} (T_f - T_0) \quad \ldots\ldots [6]$$

since $m = \rho_u Su$. Furthermore, for gases with constant average specific heat $\bar{c}_p$

$$\Delta h = \bar{c}_p (T_f - T_0)(\rho_b/\rho_u) \quad \ldots\ldots [7]$$

in order to make the required heat conduction rate per unit area equal to $\rho_b Su \, \bar{c}_p (T_f - T_0)$. From Equations [6, 7] it is apparent that

$$\frac{\delta Su}{\bar{\lambda}/\rho_b \bar{c}_p} = 1 \quad \ldots\ldots [8]$$

where δ may now be identified with the smallest width of a heated burnt gas slab of density ρ_b which will prevent flame extinction and produce a steadily propagating one-dimensional laminar flame. For slabs of width smaller than δ, the energy per unit area in the flame front is presumably insufficient to propagate the combustion wave by thermal ignition. Equation [8] differs from Spalding's result (8) for the critical minimum size $d_{crit} = \delta$ of a uniform burnt gas slab at the adiabatic flame temperature T_f only in so far as the number 1 replaces 4 on the right-hand side. Spalding obtains the number 4 because he considers flame propagation from the hot slab in two directions (which accounts for a factor of two) and because he uses a maximum temperature gradient evaluated at the mean temperature (which accounts for another factor of two).

By an argument similar to that used in the derivation of Equation [8], we find that for a spherical source of burnt gas at the adiabatic flame temperature T_f, in an infinite combustible medium, the minimum radius r_{crit} of the sphere is determined by the relation

$$\frac{r_{crit} Su}{\bar{\lambda}/\rho_b \bar{c}_p} = 3 \quad \ldots\ldots [9]$$

Minimum Ignition Energies

The interpretation of Equation [6] which led to our identification of δ as d_{crit} for one-dimensional wave propagation may be restated as

$$\frac{h_{\min}}{A} = \bar{\lambda} \left(\frac{T_f - T_0}{\delta} \right) \left(\frac{\delta}{Su} \right) \quad \ldots\ldots [10]$$

with $h_{\min}/A$ representing the minimum thermal enthalpy per unit area required to produce a self-propagating flame; the right-hand side of Equation [10] identifies the total conduction heat transfer per unit area during the life of a width δ when the flame is propagating at the speed Su.

In spark ignition measurements, $h_{\min}$ corresponds to the minimum ignition energy, and $A = \pi d_q^2$ is the effective spherical area bounding the gas volume into which the energy $h_{\min}$ is introduced. It is customary to choose d_q equal to the quenching distance in order to make certain that all of the energy introduced by the spark remains in the combustible gas. Equation [10] now reduces to Equation [4].

References

1 Hirschfelder, J. O., et al., "The Theory of Flame Propagation IV," University of Wisconsin Report CM-756, Nov. 24, 1952.

2 Lewis, B., and von Elbe, G., "Combustion, Flames and Explosions of Gases," Academic Press, New York, 1951, pp. 351–369.

3 Linnett, J. W., Discussion of the paper "Fundamental Principles of Flammability and Ignition," by B. Lewis and G. von Elbe, "Selected Combustion Problems II," Butterworths Scientific Publications, London, 1956, pp. 139–143.

4 Burgoyne, J. H., and Weinberg, F. J., "Determination of

[4] Numbers in parentheses indicate References at end of paper.

the Distribution of Some Parameters Across the Combustion Zone of a Flat Flame," *Proceedings of the Royal Society of London*, Series A, vol. 224, 1954, pp. 286–308.

5 Burgoyne, J. H., and Weinberg, F. J., "Excess Energy Hypothesis of Flame Behavior," *Fuel*, vol. 33, 1954, pp. 436–447.

6 Burgoyne, J. H., and Weinberg, F. J., "Excess Energy Hypothesis of Flame Behavior—Discussion of Basic Assumptions," *Fuel*, vol. 34, 1955, pp. 351–355.

7 Spalding, D. B., "An Examination of the Excess Enthalpy Hypothesis of Flame Behavior," *Fuel*, vol. 34, 1945, pp. S100–S106.

8 Spalding, D. B., "Theoretical Aspects of Flame Stabilization," *Aircraft Engineering*, vol. 25, 1953, pp. 264–268, 276.

A More Explicit Notation for the Temperature Sensitivity Coefficients of Solid Rocket Propellants

G. W. BATCHELDER[1] and J. K. ELDER[2]

Grand Central Rocket Co., Redlands, Calif.

THERE exist in current solid propellant literature several different notations for temperature sensitivity coefficients. For example, according to Geckler and Sprenger,[3] the temperature sensitivity coefficient of chamber pressure at constant area ratio is given by

$$\pi_p = \frac{1}{p}\left(\frac{\partial p}{\partial T}\right)_K$$

On the other hand, Sutton[4] uses

$$\pi_K = \frac{1}{p}\left(\frac{\partial p}{\partial T}\right)_K$$

for this coefficient. Also some authors consider the temperature sensitivity coefficient of burning rate π_r to be a quantity obtained at constant area ratio; while others give values of π_r at constant pressure.

In order to avoid any possibility of confusion about which system is being employed, it is suggested that authors use the following more explicit notation, which has been adopted at the Grand Central Rocket Co.

$$(\pi_p)_K = \frac{1}{p}\left(\frac{\partial p}{\partial T}\right)_K \qquad (\pi_r)_K = \frac{1}{r}\left(\frac{\partial r}{\partial T}\right)_K$$

$$(\pi_c)_K = \frac{1}{Cw}\left(\frac{\partial Cw}{\partial T}\right)_K \qquad (\pi_r)_p = \frac{1}{r}\left(\frac{\partial r}{\partial T}\right)_p$$

Received Feb. 13, 1957.

[1] Head, Chemistry Department, Grand Central Rocket Co. Mem. ARS.

[2] Senior Chemist, Grand Central Rocket Co. Mem. ARS.

[3] Geckler, R. D., and Sprenger, D. F., "The Correlation of Interior Ballistic Data for Solid Propellants," JET PROPULSION, vol. 24, no. 1, 1954, pp. 22–26.

[4] Sutton, G. P., "Rocket Propulsion Elements," John Wiley and Sons, New York, 2nd edit., 1956, pp. 323–324.

Performance Characteristics of Solar Furnaces

(*Continued from page 513*)

plate receiver where $\epsilon = \epsilon_n \cos\theta$, the maximum attainable temperature may be calculated by combining Equations [29 and 30] and using the concentration ratio C' which is based upon the absorbed flux. Thus for a flat plate receiver where $\epsilon = \epsilon_n \cos\theta$

$$T_m = \left[\frac{3}{2}\frac{\eta_a \eta_r C'}{\epsilon_n}\right]^{1/4} \frac{T_s}{14.65}$$

and taking $\eta_a = 1$ and $\eta_r = 1$, $T_m = 4540$ K.

The concentration ratio, the concentration efficiency and the maximum attainable temperature for the CIT furnace are shown in Figs. 2 and 4 as solid dots. For a cavity receiver these results indicate that as far as the maximum attainable temperature and the concentration ratio are concerned, the CIT furnace corresponds to a parabolic-type furnace with a rim angle of about 40 deg, or a diameter-to-focal-length ratio of about 1.45. For a flat plate receiver, the lens furnace corresponds to a parabolic one with a rim angle of about 30 deg, or to a D-f ratio of about 1. Parabolic furnaces capable of about the same concentration ratio and maximum temperature would have a concentration efficiency considerably above that for the CIT furnace, or about 80 per cent.

References

1 Cabannes, F., and Le Phat Vin, A., "Calcul de la Reportition de l'Energie Solaire Reflechie par un Miroir Parabolique," *Le Journal de Physique et la Radium*, vol. 15, 1954, p. 817.

2 Farber, J., and Davis, B. I., "Analysis of Large Aperture Parabolic Mirrors for Solar Furnaces," *Journal of the Optical Society of America*, vol. 47, 1957, p. 216.

3 Thomas, R. N., "The Features of the Solar Spectrum as Imposed by the Sun," Transactions of the Conference on Solar Energy—The Scientific Basis, Tucson, 1956.

4 Trombe, F., "Technique d'Utilisation d'un Rayonnement a Haute Concentration Energetique," III Congres Inter. d'Electrothermie, Sect. VI, no. 610, 1953.

Aerodynamic Heating at Great Altitudes

(*Continued from page 526*)

Conclusions

Simplified equations can be used to obtain upper bounds for the skin temperature of an ascending rocket. These upper bounds are sufficient to choose materials for the practical design.

Acknowledgment

The author wishes to thank K. E. Gray for his assistance in the preparation of this paper.

References

1 "Handbook of Supersonic Aerodynamics," NAVORD Rep. 1488, vol. I, April 1950.

2 Krause, H. G. L., "Theoretical Foundations for a Quantitative Investigation on the Aerodynamic Heat Transfer to Cones in Hypersonic Flight," Report, Forschungsanstalt für Physik der Strahlantriebe.

3 Mangler, W., "Zusammenhang Zwischen Ebenen und Rotations—Symmetrischen Grenzschichten in Kompressiblen Flussigkeiten," *ZAMM*, vol. 28, 1948, p. 97.

4 Mirels, H., "Estimate of Slip Effect on Compressible Laminar Boundary Layer Skin Friction," NACA TN 2609, 1952.

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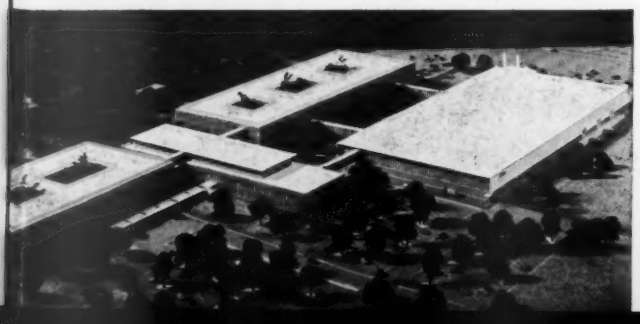

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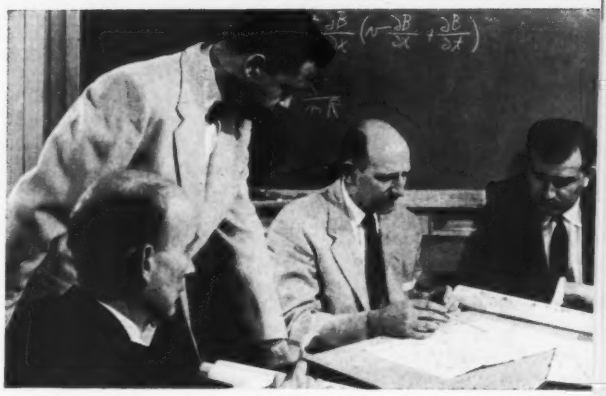

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Some Laboratory Facilities for Hypersonic Experimentation

Characteristics of Flow: / Test Facility	V_1, fps	M_1	$\frac{P_{st}}{P_0}$	$\frac{T_{st}}{T_0}$	$\frac{\rho_{st}}{\rho_0}$	Re/ft	$\dot{q}$, Btu/sec ft²	Model Diam., ft	Flow Duration, sec	Medium	Typical Installation
Intermittent wind tunnel											
Air	7,000	8	0.3	6	0.17	2×10^5	100	1	15	Air	Bklyn. Poly. Inst.
Helium	6,000	30	0.01	4	0.025	2×10^4	30	0.1	15	Helium	GE-RL; Princeton Univ.
Electrical	17,000	15	2.5	21	0.1	5×10^6	300	0.9	0.01	Air, C	ARDC
Mass accelerator											
High explosive driver	25,000	23	70	32	1.1	5×10^8	5,000	0.7	0.001	Air	GE-M&OSD
Combustion driver	16,500	15	20	21	1.0	5×10^7	2,500	0.05	0.01	Air	NACA-Ames; NOL
Electrical driver	25,000	23	70	32	1.2	5×10^8	5,000	0.1	0.01	Air	GE-M&OSD
Shock tube											
High explosive driver	20,000	3	900	45	12	5×10^8	16,000	0.2	0.0001	Air	GE-M&OSD*
Combustion driver	15,000	3	300	35	11	5×10^7	8,000	0.2	0.0005	Air	GE-M&OSD; AVCO
Shock tunnel											
High explosive driver	20,000	20	1.0	37	0.030	3×10^5	1,000	1	0.0005	Air	GE-M&OSD*
Combustion driver	15,000	15	0.5	33	0.015	10^5	500	1	0.002	Air	GE-M&OSD; CAL
Stabilized arc	10,000	3	1	35	0.015	10^5	4,000	0.5	30	H, O, C	GE-M&OSD; Giannini
Rocket exhaust	8,000	3	5	10	1	5×10^6	1,500	2	30	Comb. prod.	GE-MALTA; ABMA
Solar furnace	0	0	1	10	0.1	0	2,000	0.02	60	Air	GE-M&OSD; Fordham U. Convair
Plasma accelerator	250,000	250	20	~3,300	0.01	—	—		10^{-7}	H, He, air	GE-M&OSD*; NRL

LEGEND: M_1, Mach number referred to sea level; P_{st}, stagnation pressure; P_0, reference pressure (1 atm); T_{st}, stagnation temperature; T_0, reference temperature (294 K); ρ_{st}, stagnation density; ρ_0, reference density (0.0029 gm/cc); Re, Reynolds number; $\dot{q}$, heat transfer rate. * Indicates installation under construction.

Chart reproduced through the courtesy of General Electric Co.

Hypersonics Rubs Rough Edges off Space Flight

FLIGHT in the high supersonic regions of Mach 10 and faster creates curiously destructive forces that tear at a missile and dismember air as it slides by. To understand with an aim toward neutralizing these forces is the mission of hypersonics—a vital mission if hypersonic vehicles are ever to rush with assurance through atmosphere and space.

Intense research into this virtually unlimited area of speed has been launched at various industrial and educational facilities around the country (see table). Less than a decade old, the studies are crystallizing into a true discipline at a rate almost rivaling the velocities they study.

But the infant science is still groping in all directions for research tools—some old, others new—to simulate hypersonic flight conditions. Temperature, velocity, atmosphere composition and density are among the flight parameters that must be matched as closely as possible.

Devices to reproduce Mach 25 forces are the first goal of the scientists. At the very threshold of space travel, this is the area in which the slowest meteorites move and the earth satellite will race. Mach 27, incidentally, is the fastest that man has yet pushed any solid that retained sufficient integrity to permit measurement. (It was reached by blowing an aluminum strip away from a block of Composition B explosive; see photo.) It is also twice as fast as any man-controlled vehicle has yet flown, according to reports.

High-Pitched Research: General Electric's Missile and Ordnance Systems Department in Philadelphia probably has one of the widest ranges of mechanisms under investigation. There, in engineering offices stretching through five floors of a converted warehouse, and in a screaming test laboratory, about 100 scientists and engineers are dealing in ideas and hardware.

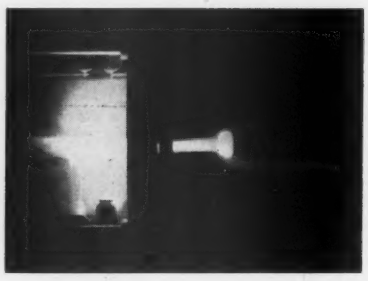
Directing the work of this Aerosciences Laboratory is Leo Steg. The physicist explained recently that so far no single piece of equipment has been found that can adequately simulate free flight in the hypersonic range for reasonable periods of time. Nor, he added, is it expected that the lab will come up with one do-it-all unit.

"Rather, with devices for studying one or perhaps two variables, and a means of relating data between devices, we hope to produce a mosaic of information on how a missile will act at Mach 25," Dr. Steg noted.

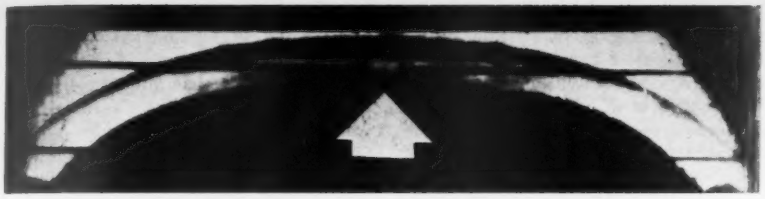
"In a solar furnace, for example, the atmosphere can be fully controlled for long times, but the temperatures are relatively low and there is no medium flow. A rocket motor exhaust gives high flow velocities but poor atmosphere. With a water-stabilized arc temperatures are very high but the chemistry again is bad. In shock tubes and tunnels, the time intervals are very short."

Still, Dr. Steg continued, for subsonic and supersonic aerodynamics, nothing is as good as a wind tunnel, probably the oldest tool in the entire hypersonic research kit. But in hypersonic areas, he observed, the scientist frequently must resort to absolute matching of states, such as temperature.

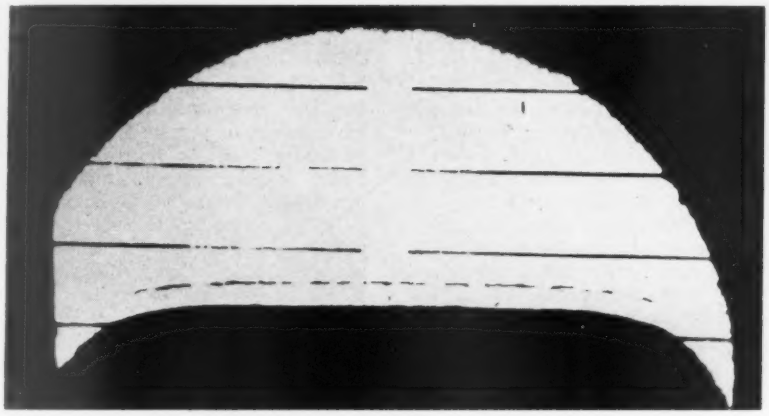
Wind tunnels can't reproduce high temperatures. In fact, with air as the flow medium, they are limited by condensation of air gases. (Nitrogen and oxygen begin to liquefy out at Mach 4.) Preheating the air and evacuating the tunnel can raise the limit to about Mach



Water-stabilized electric arc spews plasma at test specimen in open atmosphere.



About one millisecond after being blown away from block of Composition B explosive, aluminum strip (above) reaches Mach 27, fastest any solid has moved under man's influence and still retained its integrity. Leading front, straight in top photo but bending out below, is the shock wave; following front is explosion gas interface. Between fronts is the plate, complete in top photo and disintegrating below.



8, but above that value the amount of auxiliary heating equipment becomes economically and physically prohibitive. But carrying the matter one step further, by going to a light gas (very low condensation temperature), such as helium, and directing the flow through an expansion nozzle, Mach numbers up to 30 reportedly can be realized.

An outgrowth of wind tunnels is shock tubes, termed by some "the test tubes of space." Shock waves are specially valuable tools because of the high temperatures they yield; for example, a shock wave moving through normal air at Mach 25 produces heats of 12,000 K.

In operation, shock tubes use high pressure gas bursting into an evacuated tube to form the waves. Two drawbacks are manifest in the mechanism, however. Low flow Mach numbers are obtained; and the time interval in the valued test range, i.e., between the wave and the driver gas interface, is super-abbreviated, being measured in tenths of a millisecond.

The latest and most sophisticated shock device, the shock tunnel, heightens the flow Mach numbers by putting an expansion nozzle on the far end of a shock tube. Mach 25 flows and stagnation (film) temperatures can be reached for reasonable altitudes, according to reports, by exhausting the gases through a nozzle containing the test model. The force expends itself in the "dump tank." Time intervals are still very short, but with fine instrumentation much of the necessary data can be collected.

Dump tank and smaller diameter expansion nozzle (which houses test model) terminate 132-ft-long GE shock tunnel.

Wanted—Long, High Heats: Prolonged high temperature generators to determine heat effects on materials of construction and free flight mechanisms in which the test model is not held remain to complete this picture of hypersonic forces.

A number of unusual devices are in the works at GE to create super star temperatures for extended periods. One of the newest is the water-stabilized electric arc which generates a charged plasma. Continuous temperatures of 14,000 K have been reported for the plasma stream moving at 4000 fps. Also, the highest steady state heat transfer rates, about 2000 Btu/sec ft^2, are reportedly attainable, as against 800 Btu for a rocket motor.

In operation, water is swirled around the arc to protect the chamber walls and to limit the bulge of the 50,000 K electric discharge. It also serves as a source of the plasma, which is drawn off through a hollow cathode. Power requirement of the unit, with its $1\frac{1}{4}$-in.-diam anode, is 3000 kw. Under construction is a 3-in. model scheduled to consume 8000 kw. A still more powerful liquid air-stabilized arc is now being considered.

Another unique piece of equipment being built by GE is a plasma accelerator, described as a Kolb tube. This device will speed highly ionized gases to such seemingly fantastic rates as Mach 250 and calculated temperatures of the order of several hundred thousand, possibly a million, degrees K. Such conditions could be tolerated only for infinitesimal intervals of the order of 10^{-7} sec. However, Dr. Steg said, the conditions could be held down to Mach 20 or 30 for microseconds. In the other direction, he considers speeds to Mach 1000 are possible with the tube.

A. C. Kolb of the Naval Research Laboratory, inventor of the tube, states that in his device ionized gases are created by means of "high velocity, one-dimensional shock waves utilizing a high-voltage, low inductance gas discharge tube...(and driven by) magnetic fields...." The tube built at NRL is directed at studying controlled fusion reactions.

Guns Still Serve: The final area to be plumbed is free flight mechanisms, where a model is uninhibited in movement.

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As conceived at GE, free flight simulators would shoot a scale model of a missile into a controlled gas atmosphere. And the search for a gun to do the shooting is on.

Most successful to date has been the invention of Yosef A. Yoler, head of the investigation section of the aerodynamics lab: An electric gun which adds "slugs" of energy and mass directly behind a projectile as it traverses the barrel. These additions preclude the characteristic pressure and temperature decay that occur behind a round in an artillery piece. In Dr. Yoler's gun, the projectile is a nonconductive shoe designed to carry the missile model through the barrel before releasing it into the test chamber.

Electrical energy is supplied through electrodes that ring the barrel at regular intervals. Maintained at the potential just short of arcing between poles, the electrodes discharge spontaneously through the ionized gases that follow the fast moving projectile. Mass is contributed by the rubberized barrel lining that decomposes into a low molecular weight gas (mean molecular weight around 10) under the arc's influence.

These successive kicks should get the projectile up to Mach 25 or 30, says Dr. Yoler. Full-scale tests of the novel device will take place shortly.

Two other electric guns, much more ambitious than Dr. Yoler's, have been discarded after investigation as impractical at present. One, using an induction technique to accelerate a test model linearly, was given up when it was decided that a billion-watt amplifier would be necessary. In the other, using conduction to move a railed vehicle, the required million ampere current vaporized the copper contacts and shorted out the circuit before significant speeds were reached.

Chemical propellant guns are considered limited for these purposes. Initial gravitational loads can crush the test specimen. Also, explosives have a limiting velocity of about 25,000 fps in a tube, according to Dr. Yoler, and inefficiencies reduce this figure to about 15,000 fps maximum.

These are among the spectrum of mechanisms, many promising, others already discarded, that will help stretch man's reach for ever-increasing heights and speeds. When interplanetary travel is a reality, the vehicle will travel a path whose rough edges have been rubbed off by hypersonics.

New Thermal Center

CONSUMED by an omnivorous "need to know," scientists ask even more questions than young children. Focus of a major share of today's scientific curiosity, stimulated by the rapidly advancing frontier of flight, are thermophysical properties of materials.

To help satisfy this curiosity, Purdue University has established a Thermophysical Properties Research Center. Long-range objectives of the new facility are (1) to serve as an international center for research, collection, analysis, correlation and dissemination of thermophysical data, and (2) to provide what the university asserts is a unique facility and opportunity for graduate study and research.

On a more immediate basis, the center's program during its first three years will be confined to a study of the following thermophysical properties: Thermal conductivity, viscosity, specific heat, thermal emissivity, absorptivity and reflectivity, mass diffusivity, thermal diffusivity and Prandtl number.

Starting with the technically more important substances, the program will be concerned, in a selective and gradual order, with the properties of gases, liquids and solids. Criteria for selection of substances (as well as properties) to be studied will be (1) demand for information, (2) paucity or abundance of available data and (3) degree of disagreement, if any, in the given area.

Founding Fathers: Government agencies and industry are cooperating in this project by providing multiple financial support. Each sponsor contributes approximately the amount of aid he might give an individual graduate student. This enables the university to enter upon interdisciplinary programs which might otherwise be undertaken only with great difficulty.

The sponsor, in turn, takes part in and benefits from a major research program covering a broad field of application. Among those already enrolled as Founder Sponsors are American Iron and Steel Institute, Avco Mfg. Corp., Babcock & Wilcox Co., Bell Telephone Laboratories, California Research Corp., Esso Research and Engineering Co., General Electric Co., General Motors Corp., John B. Pierce Foundation, Lockheed Aircraft Corp., Office of Naval Research, Rand Corp. and Standard Oil of Indiana.

But, the university points out, this list is getting bigger all the time as others learn of the Center and its program. The program, Purdue reports, is already budgeted at $75,000 a year for the next three years.

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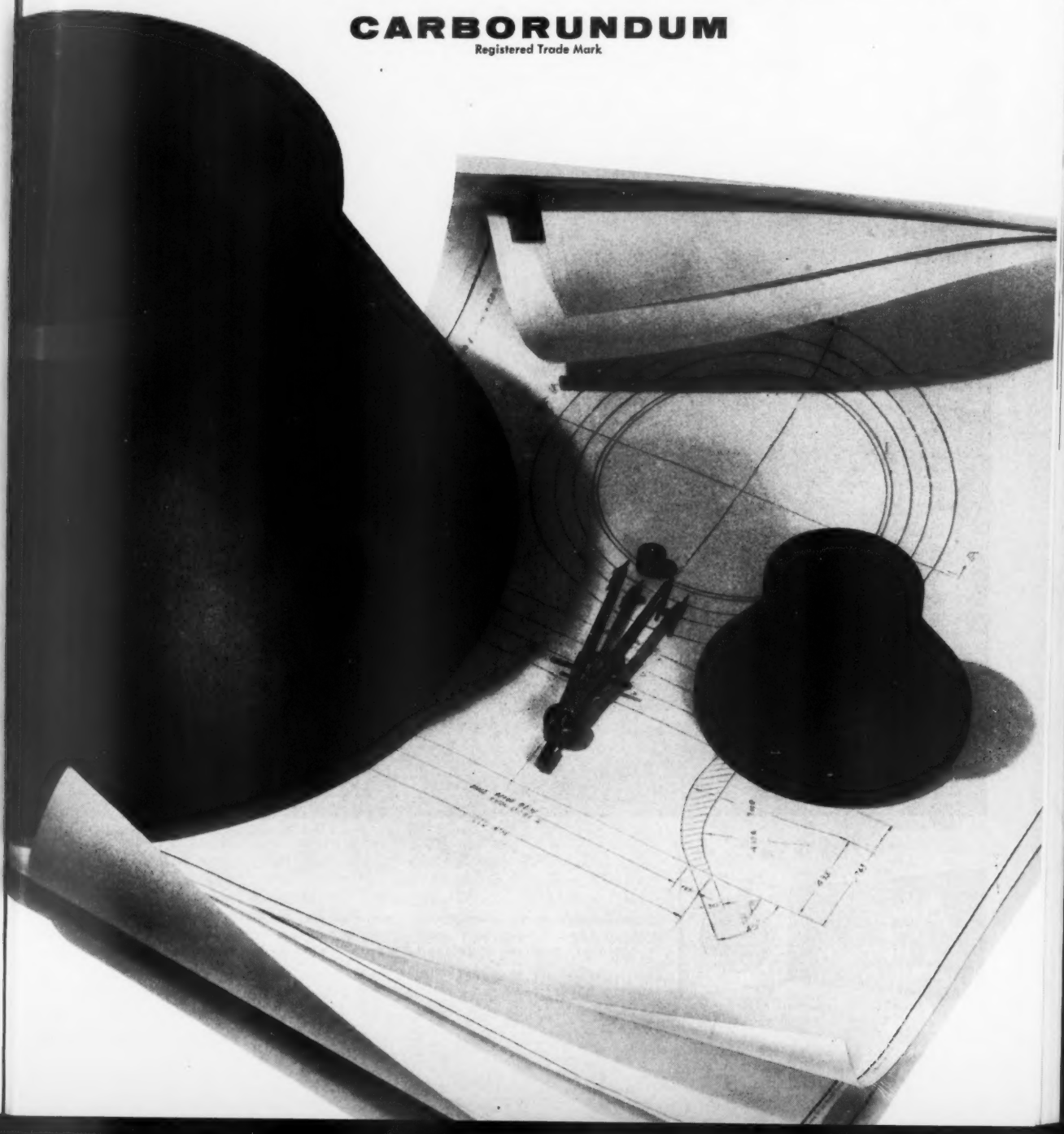

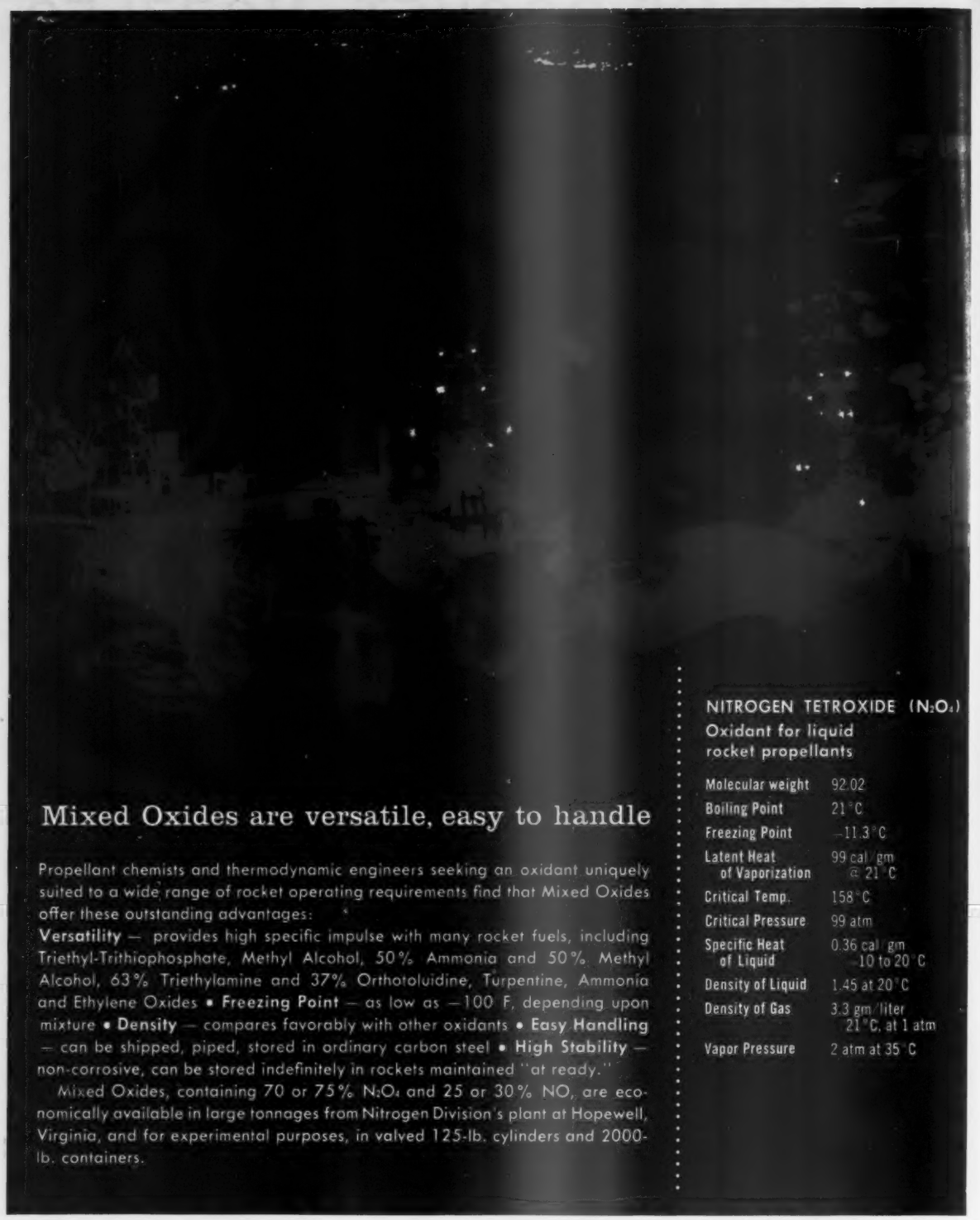

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Raytheon Silicon Extends IR-Dome Transmission

A SILICON material that can transmit infrared radiations from subzero targets and still thermally and mechanically protect delicate IR sensing units was reported last month by Raytheon Manufacturing Co. Among the applications suggested for the material are missile IR-domes for homing and mapping equipment.

Described as a solid, opaque metal, Raytheon silicon effectively extends the upper IR wave-length limit for the material from the previous 9 microns (emitted by bodies at hot water temperatures) to 11 microns (ice temperatures). The lowest wave length the material can pass is about 1.5 microns, corresponding to about 3000 F.

Further recommending the Raytheon silicon, according to project chief Harry Letaw, is the excellent thermal conductivity of the metal (one-fifth that of copper at 400 C). As a property of the nose cone of a missile, this conductivity would preclude a dome hot spot which could cause the sensing unit to develop a blind spot or home the missile on its own nose.

Mechanically, the silicon is stronger than quartz, the company claims, although it is probably more brittle. Quartz, or fused silica, is perhaps the strongest dome material used to date.

One final property, the high transmission of the incident infrared energy waves, recommends the silicon. Up to 95 per cent of the waves up to 9 microns in length will be passed. At that wave length, however, transmission is restricted to 60 per cent for a short range, picking up to between 70 and 80 per cent to the 11 micron limit for the material.

Infrared homing units have gained great favor for missiles since the remarkable performance chalked up by the Navy's air-to-air Sidewinder. Mapping by infrared techniques has been urged at least to supplement radar if not replace it completely in some areas.

Purity of the Raytheon silicon is reported to be one part in 100,000,000. The company is presently manufacturing optical parts of the material, including lenses and prisms, for IR speaker systems, Mr. Letaw said. The IR-dome program is in the development phase.

A number of substances are in competition with silicon, however. Each has characteristic advantages and disadvantages in the mechanical, thermal, transmission and wave-length range properties required. Arsenic trisulfide, with low mechanical strength, transmits infrared waves between 1.5 and 10 microns; germanium passes waves from 2 to 15 microns, but suffers from a 50 per cent transmission loss; quartz, with excellent mechanical properties, reaches only up to the 4 micron wave level (or about 600 F); and silver chloride, boasting a very wide range from 2 to 20 microns, is highly susceptible to erosion.

Sapphire (Al_2O_3), perhaps the best IR-dome material in use, can pass radiations from 250 F bodies (about 7 micron waves compared with 11 micron waves for silicon). Its thermal conductivity at room temperature is roughly one-twelfth that of copper (vs. one-half for silicon at room temperature). Its mechanical strength is comparable to silicon, Raytheon's comparison concludes.

The company sees the silicon metal permitting the "design of lightweight, simple infrared systems far less complicated than other electronic systems requiring more tubes and other parts."

Fast Fuels

FAR from a full scale war, the Korean conflict nonetheless served as a valuable reminder that military obsolescence waits for no country. Object in point: Hydrocarbon fuels.

"The conventional jet fuels of yesterday which remain stable near sea level," says California Research Corp.'s Jack Bert, "boil violently under the low pressures registered at extreme altitudes by today's supersonic jet engines, resulting in a vital loss of vehicle range." In essence, Bert notes, the hydrocarbon fuels used in Korea are now obsolete.

Realizing this, petroleum researchers went to work on the development of new and better fuels. The object was to find stable hydrocarbon propellants that would not boil in supersonic flights at altitudes of 100,000 ft or more.

Several such hydrocarbon fuels were developed and are now being released to the missile and aircraft industries. Two of the latest: MIL-F-25656 (JP-6) and MIL-F-22524. Although both fuels show a greal deal of promise, neither is yet in quantity production. Major portion of present output is still being directed into research and evaluation channels.

The new fuels differ from JP-4 principally in boiling range. JP-4 has a boiling range from about 140 to 550 F; MIL-F-25656, from about 250 to 550 F; and MIL-F-22524, from about 300 to 550 F. While JP-4 is satisfactory for subsonic jets, Bert points out, it is too

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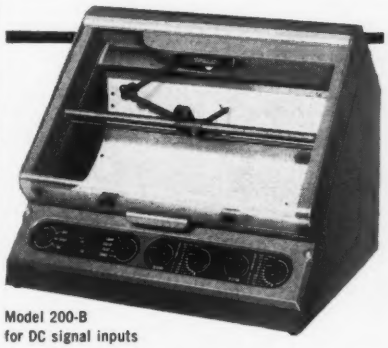

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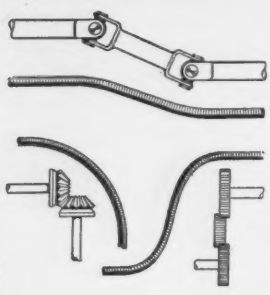

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volatile for supersonic vehicles where tank fuel temperatures sometimes run as high as 400 F.

Increased stability and lower volatility of the new fuels were obtained through refinement and use of additives. But, to achieve this, researchers had to pay the penalty of selectness. Because the freezing points of hydrocarbons increase as volatility decreases, there are comparatively few petroleum stocks available from which can be produced fuels of low volatility that still have the required and rather essential low temperature pumping characteristics.

Just where these new fuels will fit in the over-all picture no one knows at this point. That the new fuels represent a major advance over earlier ones seems evident, say the engineers. That the new fuels are far from the ultimate also seems evident.

Satellite Package Goes to 126 Miles

Using a "beefed up" motor and carrying an array of electronic equipment that will be used in the earth satellite, an Aerobee-Hi research rocket reached an altitude of 126 miles in a test firing at White Sands Proving Ground, N. M., last month.

Considerably short of the 164-mile Aerobee-Hi altitude record that the scientists expected to surpass, the firing, according to Naval Research Laboratory's John W. Townsend, Jr., who directed the test, was nevertheless extremely successful in light of the information obtained.

At the same time, Navy sources in Washington reported that The Glenn L. Martin Co., prime contractor on Project Vanguard, had rejected General Electric's first-stage engine for the satellite launching vehicle because it "did not meet specifications."

General Electric plans to correct the defects, hopes to deliver a second first-stage engine for the vehicle this month as scheduled.

New Plant, New Partner

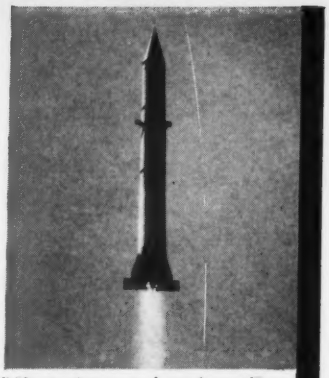
Callery Chemical Co., developer of HiCal high energy missile and jet fuel, will begin construction of a new plant in Muskogee, Okla., late this summer. Scheduled for completion by the end of 1958, the plant will be operated for the Navy as part of Project Zip.

Although still closely guarded by military security, the HiCal fuel that will be produced here is described as "a mixture of boron, hydrogen, and carbon which will multiply the range of a jet plane or missile and permit flight at altitudes substantially higher than any aircraft can reach today without rocket power."

Callery's parent organization, Mine Safety Appliances Co., has also announced that Gulf Oil Corp. will join MSA in a program of research and production in the field of boron chemistry, including high energy fuels. The joint program will be carried out by Callery.

Also in the field of high energy fuels, Metal Hydrides, Inc., reveals that it has received a second government contract, this one for $9,200,000, calling for production of sodium borohydride. Delivery, according to the company, will be made over an 18-month period.

SPARROW III, new Navy missile manufactured by Raytheon, is mounted under the wing of a jet fighter.



FICo engineers and produces the guidance for the Redstone Missile. *U.S. Army Photo*

FICo navigational equipment goes into a wide range of aircraft. *U.S. Air Force Photo*

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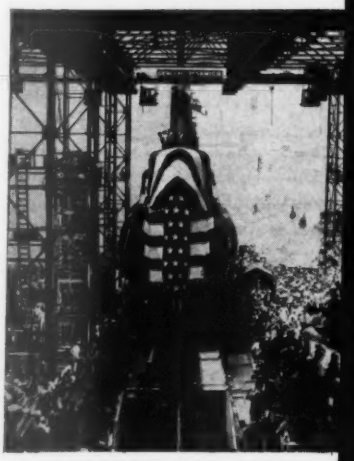
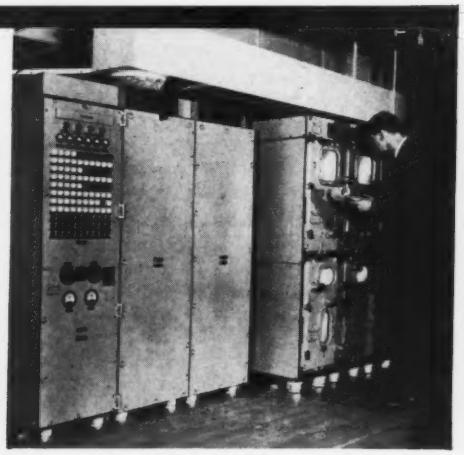
FICo is one of the foremost organizations in the United States working in the field of automatic control. Hundreds of engineers and extended precision mass production facilities enable FICo to handle complete systems contracts from start to finish.



FICo controls are used in the atomic submarine program. FICo is also working toward development of the closed-cycle gas-cooled reactor. *U.S. Navy Photo*

FICo research and design led to improved safety and arming device for Army atomic cannon. *U.S. Army Photo*



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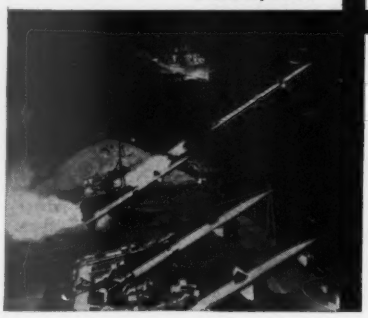

FICo launching and control order computers are used for Navy A-A missiles.—*U.S. Navy Photo*

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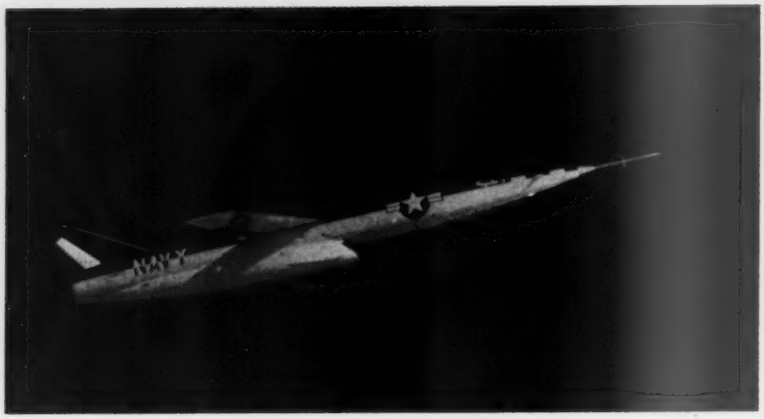

Fill-In on Regulus II

First photograph of Navy's supersonic Regulus II shows test vehicle in flight over California desert. Built by Chance Vought Aircraft, the missile is about 57 ft long and has a wing span of about 20 ft. Powered by a J-65 turbojet, present missile has exceeded velocities of Mach 1.5 and altitudes of 50,000 ft. Later versions of the missile will be equipped with a J-79 turbojet.

MISSILES

• New hassle in Washington concerns admission of the press to launching of the first earth satellite. Among others, Admiral Rawson Bennett, chief of naval research, doesn't want newsmen present. Congress is opposed to the press ban.

• Republic Aviation Corp.'s Guided Missiles Div. has received a $\$\frac{1}{2}$-million contract from General Electric Co. for assembled nose cone structural units for the ICBM.

In addition to this ICBM program and the Terrapin high altitude research rocket, Republic's Guided Missile Div. reveals that it is working on an air-to-air missile, an air-to-surface guidance system, and a project described only as "more advanced than the earth satellite."

• The West German Weather Service, according to the *Christian Science Monitor*, is planning to use small rockets loaded with silver iodide this summer in an attempt to break up costly hailstorms in Bavaria.

• Pressing for development of an anti-missile program, Lt. Gen. James M. Gavin, chief of Army Research and Development, recently repeated his belief that the IRBM and ICBM can be defended against.

• At the same time, Maj. Gen. John B. Medaris, commander of the Army Ballistic Missile Agency, pointed out that the relative superiority in the development of offensive weapons, especially guided missiles, compared to defense against them, is greater now than ever.

• Army has awarded contracts for design, development and fabrication of prototype arming devices for Bomarc and Redstone missiles to Erco Div. of ACF Industries, Inc.

• UNIVAC Div. of Sperry-Rand Corp. has received a $5-million contract to produce a guidance system for use in the Titan ICBM and Thor IRBM.

• In a recent press dispatch, Walter Dornberger, of V-2 fame and consultant to Bell Aircraft, was quoted as saying that mail via guided missile and television from outer space could be a reality in the not too distant future were it not for a lack of research funds.

• Navy has disclosed the existance of a new rocket-powered missile named Zuni. Missile costs only $150 and is said to have twice the velocity of the World War II weapon it replaces. Zuni can be used either as an air-to-air missile against enemy jets or as an air-to-surface weapon against pillboxes and tanks. A folding fin solid propellant rocket, it is launched from a jettisonable, underwing device which holds four of the non-nuclear Zunis.

• In a cooperative effort with the Air Force, the Army Chemical Corps has developed a new, stainless steel, 1500-gal trailer designed specifically for filling and emptying nitric acid from missiles.

• Speaking before the American Mathematical Society, ARS Director Krafft A. Ehricke discussed the use of gravita-

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SPECIFICATIONS:

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35 watts, 400 cycles, 115 volts, single phase
0.6 gal. per min. at 2000 psi hydraulic pressure

Regulation: ± 5% voltage and frequency

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Weight:	9.5 pounds
Size:	6.14 in. diam., 6.74 in. long

Ground power: compressed air

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This auxiliary power system is an example of AiResearch capability in the missile field. Inquiries are invited regarding missile components and sub-systems relating to air data, heat transfer, electro-mechanical, auxiliary power, valves, controls and instruments.

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tional pull from the moon to "whip" a space vehicle from earth into the orbit of Mars or Venus, thereby effecting a significant saving in fuel.

• Court martial of Col. John C. Nickerson (JET PROPULSION, April 1957, p. 429) is scheduled to get under way on May 15.

• In a recent speech on the Senate floor, Sen. Henry Jackson (D., Wash.) declared that Russia is developing an ICBM that will travel 5500 miles in 30 min, an IRBM that will cover 1500 miles in 10 min and has in working operation a 200-mile submarine-launched missile.

• Aerojet-General Corp. has signed an agreement with D. Napier & Son Ltd. (England) for the exchange of technical knowledge on liquid fuel rocket engines.

• To furnish atomic firepower necessary to reinforce the defense capacity of ground forces, the Army is organizing Atomic Support Commands armed with Honest John rockets and Corporal guided missiles.

• At the same time, according to Defense Secretary Charles E. Wilson, the Dept. of Defense has begun deployment of nuclear weapons within the U. S. for air defense purposes. First such weapon is an air-to-air rocket; next will come surface-to-air missiles Talos and Nike-Hercules.

• Scheduled for completion late in 1960, Navy's first nuclear-powered guided missile cruiser will be named Long Beach. Ship will be built by Bethlehem Steel Co. while General Electric Co. will supply the main propulsion turbines and gears and Westinghouse will produce the nuclear reactors.

• Northern Ordnance, Inc., has received a $7-million Navy contract to supply gun mounts for new guided missile destroyers and frigates and a $2½-million Navy contract for production of launching systems for the Terrier missile.

• "Project Snooper: A Program for Reconnaissance of the Solar System with Ion Propelled Vehicles," a paper delivered at the recent ARS Meeting in Washington by M. I. Willinski and E. C. Orr of Rocketdyne Div. of North American Aviation, has taken on added significance with the announcement that the Air Force has awarded Rocketdyne a $50,000-a-year contract to explore the use of ions "as a possible source of power" for space ships and missiles.

• Washington expects the Air Force Thor to be ready in a few months. The 1500-mile missiles will be equipped with nuclear warheads and are to be based in Europe.

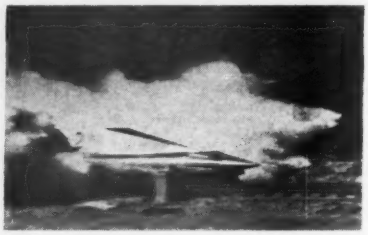
• Meanwhile, the Ding-Dong (MB-1) air-to-air missile with a nuclear warhead is reportedly arming present jet interceptors such as the F-102, F-89J and F-101B. Stockpiles of the atom-tipped missiles will be stored at various interceptor bases around the country. It was stated that the system is safe and will pose no hazards. However, a jet interceptor reportedly armed with Ding-Dong was lost in the western mountains and searchers were warned to stay away from the ship if found.

• At an ARS meeting in Huntsville, H. W. Ritchey stated that Thiokol's Redstone Div. had built and test fired the largest solid propellant rocket. This rocket is said to have compared in size with a liquid propellant rocket.

• General Electric Co. will build a closed-circuit color TV system for installation at the Florida test range. The system will give a close-up view of missile launchings and be able to follow missiles up to altitudes of possibly 100,000 ft. Cost of the CCC-TV system is estimated at between $25,000 and $100,000. In another GE contract, $83 million will be spent for electronic guidance equipment for the Atlas ICBM. Atlas is reported to be near a flight test and first firing is expected to take place within a few months. Operational status, however, may be several years off.

• The Air Force has told industry that more and cheaper missiles are needed for national defense. However, missiles have to mature, it was said, and industry will have to work to improve reliability.

• The view that space travel will be commonplace within the next 50 years is held by Captain Eddie Rickenbacker. The famed air ace made the prediction at a recent Philadelphia talk.



• Additional details have been given of the North American Aviation rocket engine used on sleds at Edwards and Holloman ABB. Burning lox and alcohol, the engines produce 35,000–50,000 lb thrust. Propellants are pressurized at 3000 psi and the mixture burns at 4700 F. In a recent test (photo) the rocket accelerated a 5000-lb sled to a speed of 900 mph in 4.2 sec. One of the engines used at Edwards was fired over 120 times.

• On another track, SNORT at China Lake, Calif., Aerojet-General has operated a liquid propellant rocket sled using red fuming nitric acid and JP-X

Dr. Lloyd H. Wilson (left), Thermodynamics Section engineer, discusses comparisons between theory and free flight test experimental data on boundary layer transition in hypersonic flow with Maurice Tucker (center), head of the Aero and Thermodynamics Department, and Thermodynamicist Karl G. Reseck.

MISSILE SYSTEMS THERMODYNAMICS

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C G Holschuh

SAMUEL AGABIAN has been appointed Manager of the Air Armament Division. Formerly works manager, Mr. Agabian is an Annapolis graduate and former Marine Corps officer. His work at Sperry has included responsibility for computing gunsights, bombsights, antiaircraft devices, radar and infrared developments.

AIR ARMAMENT

Air-to-air missiles and systems
Air-to-surface missiles
Airborne radars
Airborne beacons
Airborne electronic countermeasures
Bombing-navigation systems
Aircraft fire control radars
Airborne inertial systems

MYRON D. LOCKWOOD, manager of the Surface Armament Division, was formerly a systems engineering director. A World War II Lt. Col. of Artillery, and military-technical advisor at M.I.T., Mr. Lockwood has been associated with Sperry projects in underwater torpedo fire controls, guidance computers for missiles, antiaircraft control systems and inertial navigation equipment.

SURFACE ARMAMENT

Surface-to-surface missiles
Surface-to-air missiles
Ground and shipboard search radars
Ground and ship tracking radars
Battlefield surveillance equipment
Mortar and artillery locators
Land, ship and submarine fire control systems
Computers
Land and ship-based transmitters
Weapon direction systems
Ground and ship-based electronic countermeasures

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(40 per cent UDMH and 60 per cent JP-4) with a starting shot of aniline and furfuryl alcohol. The motor delivers 35,000-lb thrust and uses a gas pressurized system with a ceramic-lined chamber. Aerojet is now building a rocket engine and tankage for the SMART track at Hurricane Mesa, Utah.

• We can now send a rocket 2000 miles into space and recover payloads for scientific research. In a recent symposium held at RIAS, Inc., subsidiary of The Martin Co., it was proposed to send sheets of photo film into space to record primary cosmic ray intensities. Rocket components now available could project a 150-lb payload to 2000 miles for such a project.

• First stage of the Lockheed X-17 test vehicle (JET PROPULSION, March 1957, p. 299) was developed by Thiokol Chemical Corp. It is a modification of the Sergeant solid propellant rocket motor. Second stage consists of three solid propellant Recruit rocket engines, also developed by Thiokol. A single Recruit rocket makes up the third stage.

Thiokol also has revealed that it has under development or in production rocket engines for the Lacrosse, Nike-Hercules, Matador "B," Falcon and Terrapin.

AIRCRAFT

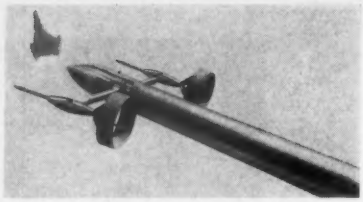
• Republic Aviation Corp. has obtained a license to manufacture Sud-Aviation's gas turbine helicopter, Alouette II (photo).

• On a recent flight from Seattle to Baltimore, prototype of the Boeing 707 jet airliner averaged 612 mph over the 2330-mile route.

• Scheduled for use on the Lockheed Electra sometime in 1958, the Allison 501-D13 propjet engine is now being flight tested in a converted twin-engine commercial airliner.

• General Dynamics Corp. has awarded General Electric a $20-million contract to make engines for Convair's future jet transport.

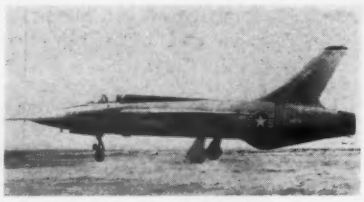
• Under Navy contract, Solar Aircraft Co. will carry out a value analysis of the company's 50-hp Mars gas turbine engine.



• Task Corp. has developed a special wind vane for Ryan Aeronautical Co. Mounted on a nose boom, the unit (photo) will be used in the measurement of angles of attack and sideslip at the relatively low airspeeds experienced in VTOL flight.

• Chance Vought's F8U-1 Crusader has completed its Fleet Introduction Programs and is being delivered to Navy squadrons for operational duty.

• Pratt & Whitney's J-57 and J-75 have become the first American-made jet engines certified by the Civil Aeronautics Board for commercial use by airlines.



• Scheduled to reach its production peak in 1958, Republic's F-105 Thunderstreak (photo) fighter-bomber will be powered by a Pratt & Whitney J-75 turbojet and be capable of carrying a nuclear bomb.

• Lycoming claims its new T-55 engine is the most powerful free power-turbine aircraft engine ever developed in America.

• Kollsman Instrument Corp. says its Integrated Flight Instrument System will be standard instrumentation on the new Convair 880.

• Australian air force plans to use F-104 fighters equipped with J-79 turbojet engines.

• Garrett Corp. will supply actuating systems for Convair's B-58 supersonic bomber.

• Lockheed will build a large amount of tooling on the new Fairchild F-27 propjet transport under an $800,000 contract from Fairchild.

• The Air Force has contracted to buy $13,300,000 worth of J-75 turbojet engines from Pratt & Whitney.

• Army Transportation Corps has awarded Kellett Aircraft Corp. a contract for the design and development of a two-man helicopter.

• Douglas Aircraft Co. has developed a device which prevents jet engines from sucking up foreign objects off

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In less than half-a-century, BUDD has grown to an organization with more than 20,000 employees and a world-wide reputation for metal engineering FIRSTS unequaled in the industry. A prime contractor for both the automobile manufacturers and railroads, we have always been regarded as pioneers in the development of metals research programs—not only for industry, but for the wide variety of military and research equipment used for the protection of our country.

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If you are experienced in aircraft and missile structures, jet and nuclear propulsion elements, or nuclear energy applications . . . tell us about yourself! A complete resume of your educational and work background will be appreciated and held in strictest confidence. Take your choice of the four following locations and write today.

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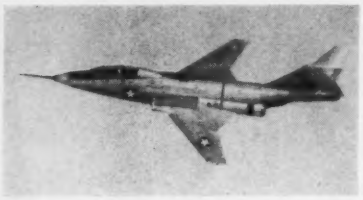
the ground. Tagged a "Blowaway Jet," the unit breaks up or dissipates the whirling vortex which forms ahead of jet engines before it develops enough power to toss foreign material into the jet inlet. The device, says Douglas, will be used on all DC-8 airliners.



• McDonnell Aircraft Corp. says that its newest jet interceptor, the F-101B Voodoo (photo), has successfully completed its first test flight.

• Douglas Aircraft Co. has proposed a new utility assault aircraft to the Navy. Designated Model 1906A. the plane would be powered by four Lycoming T-55 turboprop engines.

• Temco Aircraft Corp. has ordered 30 ejection seats from Hardman Tool & Engineering Co. for the Temco TT-1 primary jet trainer.

• Aerojet-General Corp. claims that its AeroBrake thrust-reverser has been successfully tested on an Allison J-71 jet engine.

• Another thrust-reverser, this one by Curtiss-Wright Corp., is said to shorten landing roll up to 50 per cent.

• Air Force has decided to halt work on Douglas's C-132 turboprop air transport.

• Reaction Motors, Inc., will produce the propulsion system for the X-15 manned rocket aircraft now under development at North American Aviation. The RMI powerplant is described only as a large liquid propellant rocket engine.

• Lockheed's experimental U-2 jet aircraft crashed last month in a remote desert section of eastern Nevada. Pilot Robert L. Sieker was reported killed in the crash. The plane was designed as an upper air research vehicle for the National Advisory Committee for Aeronautics.

COMPANIES

• Bristol, Tenn., will be the site of a new 150,000 sq ft plant for Sperry Rand Corp. About 1200 men will work here on naval ordnance systems, air navigation equipment and missile system equipment.

• Test sets for missile guidance computer units will be produced by Consolidated Avionics Corp., Westbury, L. I., N. Y., under a $250,000 contract with American Bosch Arma Corp. The test sets will be used to check out missile-borne computer units prior to installation in inertial navigational systems of completed missiles.

• In operation at Ramo-Wooldridge Corp., a new data reduction center rapidly converts telemetered test data into forms suitable for engineering analysis.

• Rocketdyne has taken full occupancy of its new $4-million factory at Neosho, Mo., where it will manufacture rocket engines for the ballistic missile program. Work is still under way at the test station area of the $13.2-million facility. Total employment is expected to reach 1000 by the end of 1957.

• Kama Instrument Corp., Mineola, N. Y., manufacturer of fine wire wound components for the Nike, is to become a subsidiary of the Narda Corp., also of Mineola.

• General Electric Co. will produce electronics for the ICBM at a new Utica, N. Y., facility formerly used by the Oneida Knitting Mill.

• Establishment of a new firm, DATICS Corp. (Fort Worth, Tex.), was announced. The firm will offer services in the electronic computing and data processing field.

• The fluorocarbon, Kel-F, will henceforth be manufactured by the Minnesota Mining and Manufacturing Co. The firm will take over the Kel-F manufacturing facilities adjacent to developers M. W. Kellogg in Jersey City, N. J.

• Development of a small radio theodolite will begin under a $1.2-million contract by Servo Corp. of America, New Hyde Park, N. Y. The instrument is to track automatically a radiosonde transmitter of 50 milliwatts power from a distance of 100 miles.

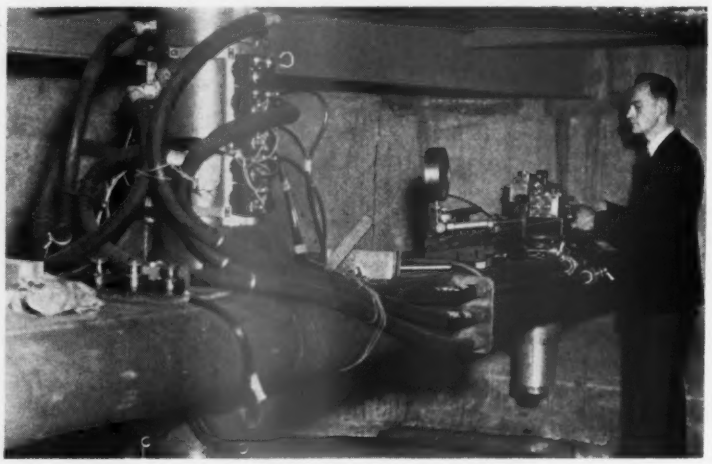
• A new reconnaissance systems laboratory has been established at Mountain View, Calif., by Sylvania Electric Products. The lab will engage in research and development work on new techniques and electronic systems for intercepting radio signals.

INSTITUTIONS

• A series of special summer programs has been announced by the Massachusetts Institute of Technology. Topics of missile interest include: Modern developments in combustion, missile aerodynamics, turbomachinery and thermodynamics.

• As a follow-up to last year's successful conference on "Metals at High Temperatures," Gordon Research Conferences is planning another metals symposium this year. The second conference is now scheduled for June 17–21 at New Hampton School, New Hampton, N. H. Further information may be obtained by writing to W. George Parks, Director, Gordon Research Conferences, University of Rhode Island, Kingston, R. I.

• Subject of the spring meeting of the Commercial Chemical Development Assn., to be held May 13–14 at French Lick, Ind., will be "What the Rocket and Missile Program Means to the Chemical Industry." Discussions will center on growing requirements of the rocket and missile program for fuels, oxidizers and propellants in general.



New Centrifuge

Technician adjusts test equipment mounted on auxiliary turntable carried on one arm of a new 100-g centrifuge at Flight Development Establishment of D. Napier & Son Ltd., England. Used for testing missile components, the centrifuge, Napier claims, is the most powerful and versatile in England.

Getting specific about gravity!

Falling apples fascinated Sir Isaac Newton. No doubt he enjoyed a few of them while devising his famous gravitational formulas. Newton's concern was with what came down, whereas aviation engineers today are primarily concerned with what goes up. Even so, the gravitational challenge is the same.

A jet plane, intercontinental missile—or anything that moves — usually leaves the design stage too heavy for optimum performance. To be specific — the specific gravity of the material of construction is too high.

Now, with Titanium, the design engineer can capture the strength of alloy steel at barely more than half the weight. What's more, Titanium is unaffected by most corrosives . . . and is impervious to the deadly attack of sea water and marine atmospheres. Its coefficient of expansion is low . . . and it can withstand long-time operating temperatures as high as 1000°F.

All types of Titanium mill products, from foil to seamless tubing, are made by TMCA. With production going up and prices going down, now is a good time to design with Titanium. Technical literature on Titanium is available just by asking.

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Air Force crew readies sled equipment prior to acceleration tests. Inset: Fairchild Motion Analysis Camera was focused on forward shoe. With lens pointing forward, it took clear, steady pictures at 120g's initial, 45g's average state. Photo courtesy Coleman Engineering Company, Inc.

Steady pictures at 120g's

Fairchild high-speed camera records shoe action in rocket sled test

If you have ever analyzed high-speed phenomena, you can appreciate this Fairchild Motion Analysis Camera's performance in a recent Air Force rocket sled test. With lens pointing forward, the camera caught the action of the sled shoe without film jump or flutter — in spite of the high acceleration, vibration and shock.

Designed for airborne and vehicular applications, the Model HS100 has consistently taken good pictures under the following environmental conditions:

Shock:	165g's repeatedly
Vibration:	20g's at 10 and 50 cycles 10g's at 100, 200 and 500 cycles
Temperature:	−65°F to 194°F (without heaters)

Only 11 lbs. in weight, the Model HS100 has motor ranges of 16-100, 32-250, 80-2000, 700-2400 pictures per second with stop-start operation at speeds up to 450 pps. Lenses range from 3.7mm to 152mm.

Like to know more about the Fairchild HS100 and high speed photography? Mail the coupon today.

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FOREIGN

England: U. S. will supply Britain with IRBM's to be based in England. Nuclear warheads for the missiles will be stored nearby but under U. S. control. Meanwhile, Britain is going heavy on missiles and light on bombers. Battleships will be scrapped; the draft will be stopped by 1960; bomber production will be curtailed; and interceptors may be cut back.

• The Society of British Aircraft Constructors revealed in March that 400 companies—the greater part of Britain's aircraft industry—are engaged in guided weapon work. "It was logical to assume that in view of the ten-year development plan initiated in 1947, our guided weapons might be operational in the 'not too far distant future.'"

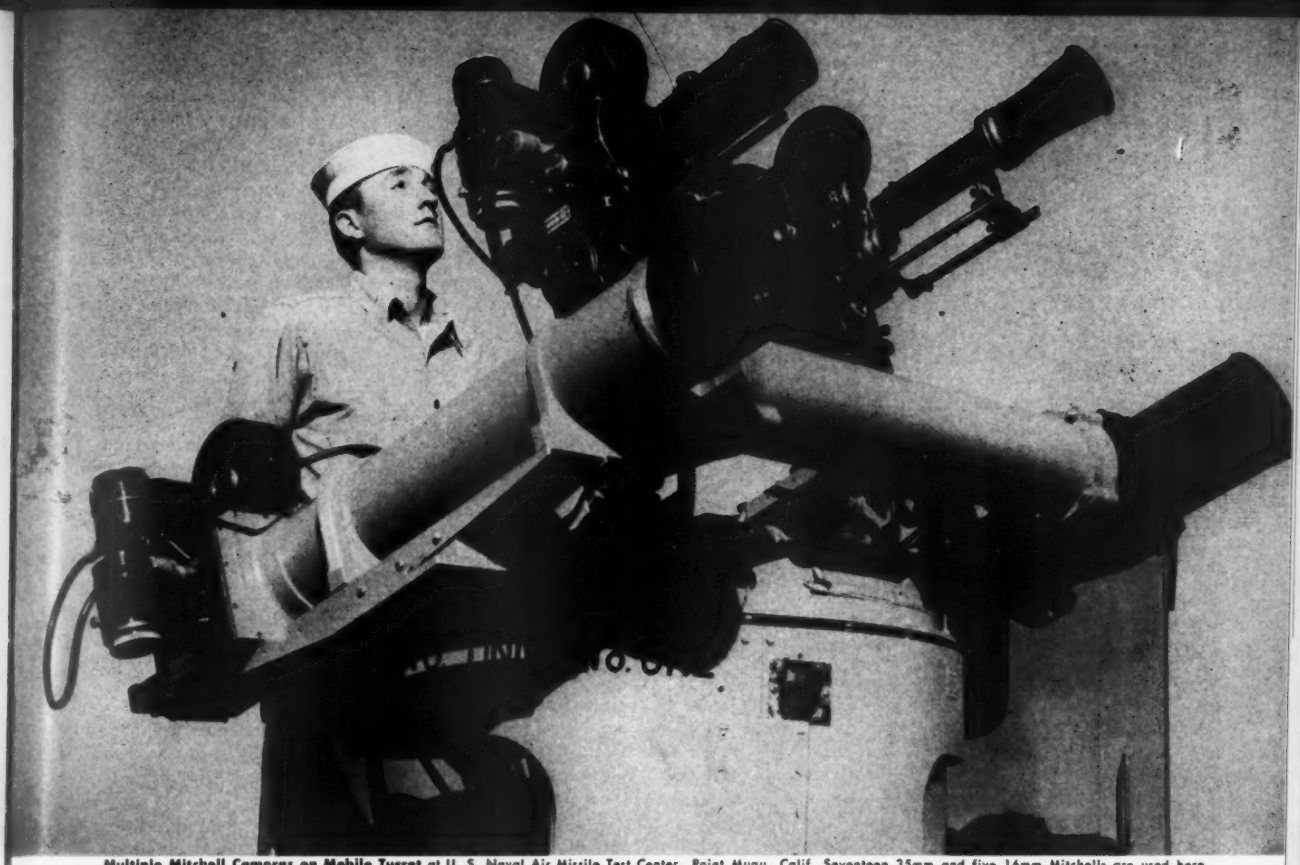
• Bristol Aircraft Co. is testing the Bobbin, a recoverable ramjet missile, at Weapons Research Range in Woomera, Australia.

• An advanced party of 300 servicemen was scheduled to land on the lonely St. Kilda island group in the Outer Hebrides last month to prepare the way for establishment of a base for guided weapon tracking in connection with plans to establish a test and training range in the South Uist area. The St. Kilda group is on the flank of the proposed range. As a first step, two observation stations will be set up on high points on the main island of Hirta. The eventual permanent staff, mainly army personnel, is foreseen at from 40 to 50.

• De Havillands announced that they are to carry on with their Gyron engine, D Gy 2, as a private venture following a decision by the Ministry of Supply to discontinue official support, which has extended over the last four years. The engine has an "approved static thrust" of 20,000 lb without reheat, increased to 25,000 lb with reheat. It is believed to be more powerful than any other in the world and was developed, starting late in 1950, as a powerplant for supersonic aircraft capable of Mach 3.

• The Short SC1, Britain's first vertical take-off jet plane (JET PROPULSION, February 1957, p. 193), made its maiden flight last month at the Ministry of Supply's experimental field at Boscombe Down, Wiltshire. Tom Brooke-Smith, 38, the firm's chief test pilot, took her round on several circuits at 2000 ft. Only one of the Rolls Royce RB 108 small high thrust jet engines appeared to be in use. The rest are believed to be used to sustain vertical flight.

Russia: The possibility of launching satellites from multistep vehicles based on turbojet and ramjet first and second stages is discussed by the chairman of the astronautical section of the Central Aeronautic Club of the USSR, M. Varvarov, in an article in



Multiple Mitchell Cameras on Mobile Turret at U. S. Naval Air Missile Test Center, Point Mugu, Calif. Seventeen 35mm and five 16mm Mitchells are used here.

CAMERA BECOMES BASIC RESEARCH TOOL

Official U. S. Army Photograph

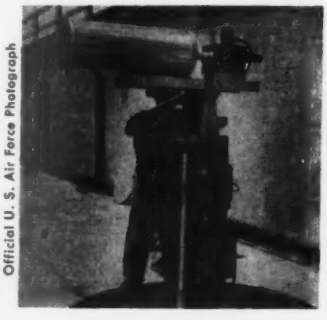
200 Mitchell Cameras, mostly high-speed models, are in use here at White Sands Proving Ground, New Mexico.

Official U. S. Navy Photograph

Powered Tracking Mount has Mitchell Cameras; over 50 Mitchells are used at U.S. Naval Ordnance Test Station, Inyokern, Calif.

Mitchell Telephoto Tracking Camera in use at Air Force Missile Test Center, Cape Canaveral, Florida.

One of 12 Mitchell cameras used to track missiles at Holloman Air Development Center, Alamogordo, New Mexico.



Official U. S. Air Force Photograph

Official U. S. Air Force Photograph

Vital Projects Now Heavy Users of Motion Picture Cameras With Flexible Performance Range

Accelerated project work has today put increased demands upon motion picture equipment. Because of the need for a camera which can perform under a broad range of research and development requirements, the Mitchell Camera has today become the standard *basic* motion picture camera used in projects in this country and abroad.

No other single camera can be used so flexibly, under such extreme filming conditions, and for such a broad range of cinematography as can a Mitchell Camera. In one location, alone, 200 Mitchell 35mm and 16mm cameras are now in use at White Sands Proving Ground.

Write today on your letterhead for information on the Mitchell Camera line.

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New REVERE FUEL METER

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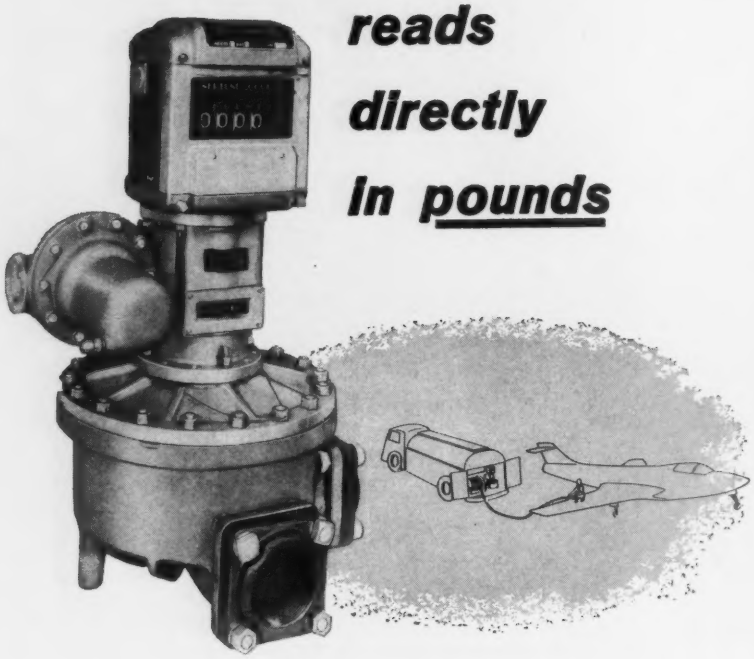


No more separate sampling of military aviation fuels to determine specific gravity . . . no more computations to convert gallons into pounds. This new Revere Gravimetric Meter measures fuel delivered from tank truck or fueling pit to plane directly in pounds . . . in one easy step.

Because fuel energy is proportional to weight rather than volume, the new meter facilitates precision flight planning. It also minimizes errors in weight-and-balance computations.

It contains two measuring elements . . . a highly accurate Neptune Red Seal volumetric meter, coupled with a sensitive Revere Densitometer which continuously measures the density of the fuel passing through the meter. The Gravimetric Meter automatically compensates for changes in density caused by temperature variation or change in type of fuel, ranging from 5.4 to 7.4 pounds per gallon. Accurate to 0.5% of total delivery. Flow range is 250 to 2,200 ppm at density of 7.4 ppg; 250 to 1,600 ppm at 5.4 ppg. Other flow ranges available. Meets applicable sections of MIL Specification F-8615.

Write today for Bulletin 1060 . . . full details of the Revere Gravimetric Meter for Ground Fueling

Revere CORPORATION OF AMERICA 13

WALLINGFORD, CONNECTICUT A Subsidiary of Neptune Meter Company

Science and Life (published by Pravda). He claims that this would offer great economies in fuel and simplify control.

Two alternatives are offered. In the first, turbojet motors are suspended in pods below the large wings of a rocket vehicle and sustain it in flight through the denser layers of the atmosphere to a height of 20 to 25 km, by which time, he claims, it might reach a speed of 2000 km/hr. The turbojets would then be jettisoned and climb would be sustained by ramjets which would take the vehicle to a height of 35–40 km and give it a speed of 5000 km/hr. The ramjets would then also be jettisoned and the rocket would continue its upward climb with liquid-fueled motors either single or multistaged.

Pointing out that it is not always economical to jettison motors in this fashion, Varvarov suggests as his second alternative that a series of vehicles might be used. The rocket or rockets would be carried on the back of a winged ramjet plane that would in turn be carried on the back of a larger turbojet plane. The performance to be aimed at for the various stages would be the same as with the first alternative.

The second plan, says Varvarov, would be particularly appropriate when atomic motors become available. Either plan would make it possible to consider construction of an ISZ (artificial earth satellite) of considerably greater weight and dimensions than has been contemplated hitherto.

• U. S. reports say that Russia has already fired 50 long-range (750–1000 mile) rockets in tests. West German sources claim that the USSR is setting up nuclear missile launching sites in East Germany, Czechoslovakia and Hungary. At the same time the Kremlin is cautioning Sweden, Norway, Denmark, England and France against permitting the U. S. to set up missile bases in their countries.

• With the Red ICBM said to be on a "crash basis," the IRBM operation is being set up as an independent "rocket corps."

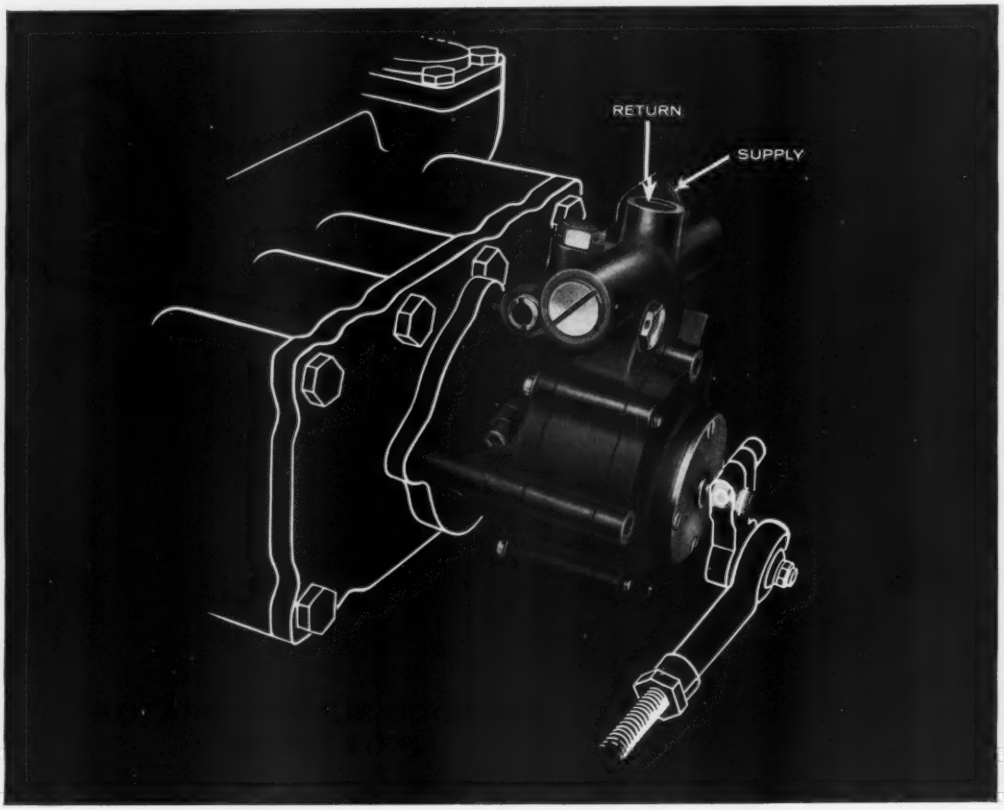
• Latest reports of the Russian satellite program state that its payload will be some 50–100 lb in weight and will be launched in a pole-to-pole orbit.

Germany: The new German army under NATO has asked for nuclear armed missiles, presumably the long-range variety, to counter the growing Soviet threat.

France: Two large SEPR solid propellant rockets have been publicly viewed. Largest is the Model 73 booster which develops 45,000-lb thrust for 4 sec. Total weight is 1630 lb. Propellant I_{sp} is 192 sec. Model

(*Continued on page 574*)

NEW FAIL-SAFE, DIRT-INSENSITIVE COMPONENT FOR CONTROL SYSTEM DESIGNERS



The Type 141F12 Rotary Torque Booster is a fail-safe hydraulic amplifier. It is commonly "sandwiched" between a turbojet engine control and the throttle lever — reduces substantially the pilot's effort to move the throttle. In a typical installation with a fuel supply of 200 psi, the torque output to the engine control is 80 inch-pounds at an input level of 10 inch-pounds. Either fuel or oil may be used as the operating medium. Pressures from 150 to 900 psig are suitable.

Unique dirt-insensitive servo valve construction, plus double failure protection against torque feedback to throttle input, accounts for the high reliability of the Booster. Even if hydraulic power should fail, a direct mechanical link permits no-boost operation of the engine control. Construction is such that input overloads of 600 inch-pounds can be handled without damage.

Manning, Maxwell & Moore will gladly provide engineering assistance in applying the Type 141F12 Rotary Torque Booster to any installation where the torque necessary for angular positioning exceeds specified requirements.

INTERESTING OPPORTUNITIES *are now open to electrical and mechanical engineers who become associated with our Aircraft Products Division. We cordially invite you to write or phone Mr. J. W. Cross, Manning, Maxwell & Moore, Inc., Shelter Rock Lane, Danbury, Connecticut.*

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OUR AIRCRAFT PRODUCTS INCLUDE: TURBOJET ENGINE TEMPERATURE CONTROL AMPLIFIERS • ELECTRONIC AMPLIFIERS PRESSURE SWITCHES FOR ROCKETS, JET ENGINE AND AIRFRAME APPLICATIONS • PRESSURE GAUGES • THERMOCOUPLES HYDRAULIC VALVES • JET ENGINE AFTERBURNER CONTROL SYSTEMS.

Space Flight Notes

JOHN GUSTAVSON, Convair-Astronautics, Contributor

Nuclear Fusion—Energy of the Future

SEVERAL research projects on nuclear fusion are under way in this country and, no doubt, similar efforts are taking place elsewhere in the world. Project Sherwood, at Los Alamos, directed by Amasa S. Bishop, and Project Matterhorn, at Princeton, directed by Lyman Spitzer, Jr., are the best known of these. Research is also being conducted at the radiation laboratories at Berkeley and Livermore.

The great effort concentrated on the research on the nature of fusion processes and their practical application is hopefully believed to solve all energy problems. The sources of fossil fuels such as coal and oil are running short and will eventually be exhausted. Even though new oil reserves are discovered every day, no prospector will promise the supply will last for more than another hundred years at the present consumption. It seems a great waste to utilize coal and petroleum for simple burning or combustion when they can be more effectively used in the chemical industry as raw materials.

Ten years ago papers optimistically described the glorious future of a civilization based on the utilization of fission energy; today the picture has changed. Processable reserves of fissionable materials such as uranium and thorium will last only a few centuries at the expected increase in energy consumption.

Another serious problem is introduced in the form of radioactive waste from the fission reactors. Even today reactor stations must employ ingenious methods to reduce the over-all weight of radioactive end products. Fusion reactions, however, render no appreciable amount of hazardous material.

Finally, the cost per energy unit of fusion materials, such as deuterium, is only a small percentage of the cost of fissionable materials, which must be extracted from low-grade ore.

Solar energy is often mentioned as a potential energy source. There is little doubt that the collection of the heat from the sun will support the energy need of future generations, but solar energy is not sufficient as the single source.

These considerations, then, are the basis for intensive research in the scientific world on fusion.

Table 1 Fusion reactions

1)	$D + D$	$\rightarrow$	He^3	+	n +	3.25 Mev
2)	$D + D$	$\rightarrow$	T	+	p +	4 Mev
3)	$T + D$	$\rightarrow$	He^4	+	n +	17.6 Mev
4)	$He^3 + D$	$\rightarrow$	He^4	+	p +	18.3 Mev
5)	$Li^6 + D$	$\rightarrow$	$2He^4$	+	22.4 Mev	
6)	$Li^7 + p$	$\rightarrow$	$2He^4$	+	17.3 Mev	

Fusion Processes

Thermonuclear reactions, or fusion processes, are reactions between the charged nuclei of light elements. The nuclei form new elements with a mass which is almost equal to the sum of the masses of the reactants. The fraction of mass liberated by the process appears as energy in the form of radiation, or rotational and translational energy of the end products. Table 1 lists several fusion reactions.[1]

Reactions 1 and 2 compete with equal probability. Their end products can further react after 3 and 4, two processes with high energy yields.

The reacting nuclei have positive charges, and the Coulomb barrier must be penetrated before fusion can take place. One way of accomplishing this is to give the nuclei sufficient kinetic energy. The corresponding temperature equals several million degrees Kelvin. Thus we have the problem of heating the nuclei to a temperature where the energy distribution ensures a sufficient reaction rate. This operation is the ignition process.

The next problem is to maintain the rate of fusion at a level where the processes yield enough energy to account for losses to the surroundings and for the heating of new reactants. The radiation losses increase with the square of the linear dimension of the fusion chamber, while the volume, and thereby the mass of energy-producing plasma, increases with the cube. Thus a sufficiently large chamber will assure the energy balance. Such a solution is adequate for the sun and stars, but is hardly desirable for the population of the earth.

The ignition of a fusion reactor will not introduce any unknown problems. The thermonuclear bomb of today is ignited by a fission reaction, and this method could probably be applied to a reactor after development problems have been solved.

Another possible ignition method may be derived from plasma physics. (A plasma is defined as a fourth state of matter following the solid, liquid and gaseous states. A plasma is outwardly neutral, whereas the matter may be partly or completely ionized to form electrically equal amounts of ions and electrons. The conductivity can be compared with that of metals. The fluid dynamic properties resemble those of liquids. It may be surprising to realize that our universe consists mainly of matter in the plasma state. Concepts of the astrophysicists have therefore been the foundation for research in plasma physics.)

Development of arc techniques has made possible the attainment of high temperature plasma. At present the interest in arcs is focused on their possible application in gas dynamics facilities and upon their practical application in the propulsion of space vehicles. The afore-mentioned ignition of fusion reactors could be a third means of arc utilization. Fusion reactions have been observed in high intensity pulse arcs. The reaction rate was far below that required to render the process self-sustaining. However, the development of high intensity arcs may supply the answer to this problem.

The energy balance of a fusion reactor is yet a more serious problem. In the stars we find a balance maintained between the radiation pressure of the reacting nuclei in the center of the star and the gravitational compression of the outer layers. A decrease in fusion reactions with a corresponding lowering

[1] Post, Richard F., "Controlled Fusion Research—Application of the Physics of High Temperature Plasmas," *Rev. Mod. Phys.*, vol. 28, no. 3, July 1956.

PIONEERING SCIENTIFIC FRONTIERS AT GENERAL MILLS

WE START WITH PLASTIC SHEETS, END WITH STRATO DATA ANALYSIS

Building the polyethylene balloon, as shown here, is part of General Mills balloon systems service. The "full package" service, typical of our thoroughness in other areas of activity, includes: design of vehicle and instrumentation, manufacture and flight planning—including meteorological services, flight operations, telemetering, tracking and recovery, and finally, analysis of collected data.

Manned strato-balloon flights probe the mysteries of space

This is the Navy Project Strato-Lab balloon that set a new altitude record in a recent ascent at Rapid City, S. D. The fact that Commanders M. D. Ross and M. L. Lewis rose to 76,000 feet, the highest man has flown in a balloon, was incidental. Of far more importance was their demonstration that a light, comparatively inexpensive polyethylene balloon, with a gondola carrying its own atmosphere, is a feasible means of carrying human observers above the present ceiling of sustained powered flight. Manned flights to altitudes of 100,000 feet or more are possible today.

Man has flown higher in a rocket plane, but only for seconds at a time. General Mills strato-balloons can remain at controlled altitudes for days if required. (Thus, "passengers" have time to make detailed observations.) They can also be used as launching stations to give rockets a "head start" into space.

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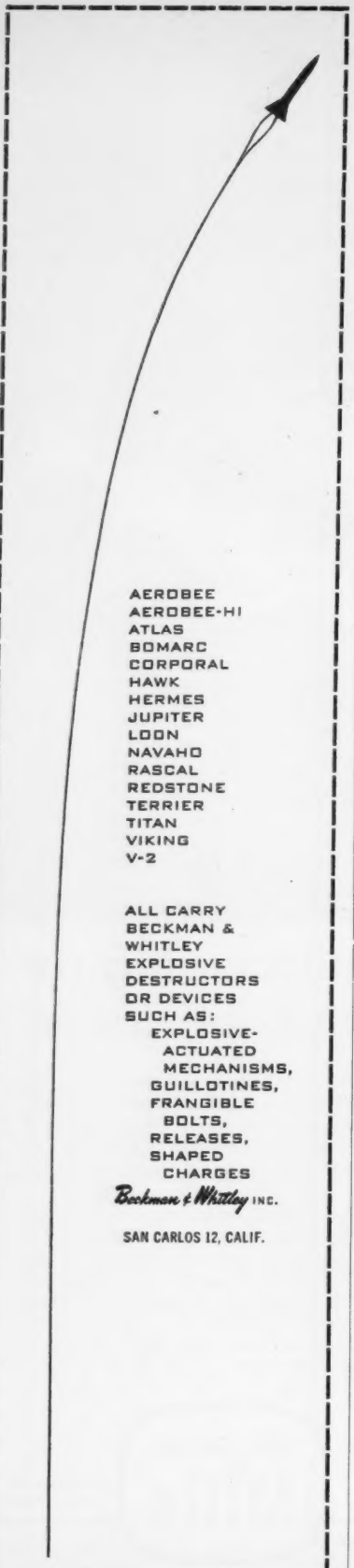


of radiation pressure will cause the star to compress. This compressing action will, however, heat the reactants, thereby increasing the rate to the former balance.

The existence of such a balance on earth is not feasible. A method for containment of the reacting plasma must be developed, and the rate of fusion must be controlled to balance the liberated energy with the losses to the walls plus the heating of the reactant feed. The amount of heat transmitted to the walls must, therefore, be kept low to maintain the reaction as well as to prevent the wall material from evaporating.

It may be seen that a temperature gradient will exist from the reaction zone in the center to the walls, which must be kept cool. The gradient is dependent upon the density, the state and the radiative properties of the plasma. Conduction and convection are negligible in the transfer. Since very low density must be maintained in the chamber in order to keep the pressure down at the elevated temperature, the gradient will be correspondingly low. The influence of the state of the plasma is to be considered only for "low" temperatures, that is, tens of thousands of degrees, where ionization can absorb energy. It is readily understood that very large chamber volumes are necessary for this undertaking.

The wall material must have a very high reflectivity. Transpiration cooling has been proposed[2] where the reactant feed is introduced into the chamber through porous walls. However, this method is not wholly adequate. Completely new techniques are needed and must be employed. For example, one may visualize liquid metal walls, which are constantly being injected tangentially and stabilized at the secondary cylindrical wall by the turbo-principle. The property requirements for such a wall include high reflectivity, low viscosity, high heat capacity, large nuclear cross section and wide liquid state range.

A wall of this type would reflect a major part of the radiation back into the reaction zone, absorb the fast neutrons produced by the fusion, and transport the absorbed heat away to a heat exchanger for primary or accessory power conversion.

With all considerations taken into account, we may conclude that a hot fusion reactor still belongs to an advanced technology of the future.

Magnetic Plasma Confinement

A controlled fusion reactor must operate at such a high temperature that the reaction power will exceed radiation losses, thus rendering the reaction self-sustaining. In order to minimize particle losses from the reaction zone, an electromagnetic method of confinement may be employed.

The plasma is highly ionized, and an electromagnetic field is capable of exerting a force upon the charged particles. One example of an electromagnetically confined plasma is the "pinch effect." Consider a plasma produced by the arc between two electrodes. A high intensity current flows through the plasma, thereby producing a strong magnetic field around the arc. The arc can now be compared with an infinite number of parallel conductors carrying the current, and exerting mutual attraction upon each other. The column must then necessarily contract. The contraction of the plasma continues until the pressure balances the electromagnetic force.

Oscillations are common in a pinched plasma; they are actually difficult to avoid. Temperature maxima will occur periodically, and thus offer the conditions for a fusion process to take place. Actual fusion reactions between a few particles have been observed. Development of strong external fields will, perhaps, make the fusion reactor a possibility.

Catalyzed Fusion

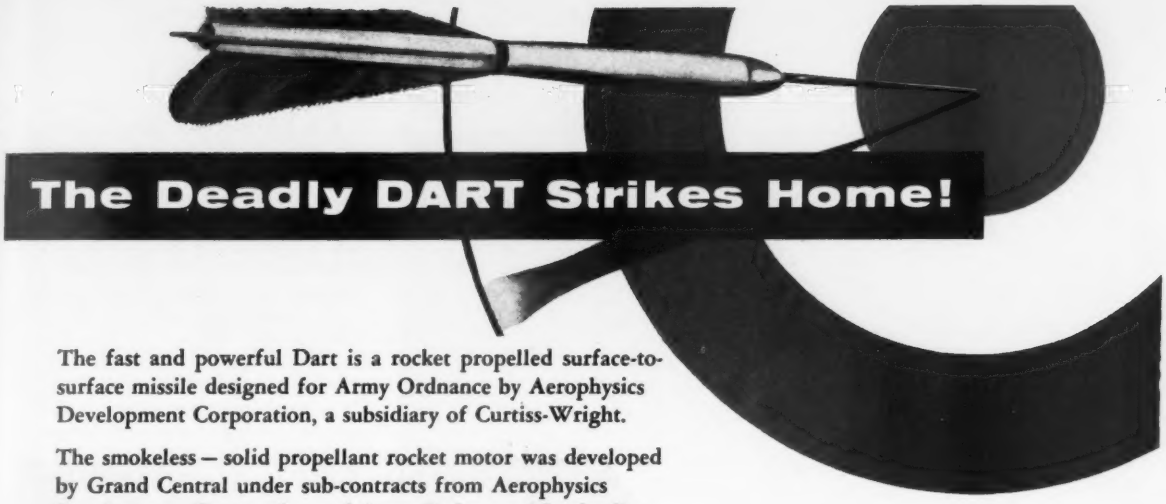
A revolutionary way to produce nuclear fusion was revealed in December 1956 at the Berkeley laboratory of the University of California.[3] A team of twelve physicists, headed by Luis W. Alvarez, were studying cessation of negative K mesons in a 10-in. hydrogen bubble chamber. (The hydrogen bubble chamber is based on a principle similar to that of the well-known Wilson cloud chamber.)

In the University of California experiment many more negative μ mesons than K mesons traversed the bubble chamber, giving the researchers opportunities to observe decay of μ^- mesons. In addition to the normal stoppings, they observed 15 cases in which it appeared that a μ^- meson came to rest in the hydrogen and gave rise to a secondary negative particle, which in turn decayed by emitting an electron.

Their explanation was that the μ^- meson catalyzed a fusion between a deuteron and a proton, thereby releasing an energy of 5.4 Mev, which "rejuvenated" the μ^- meson. The μ^- meson changes place with the hydrogen electron, and forms a mesic atom.

[2] Tsien, Hsue-shen, "Thermonuclear Power Plants," JET PROPULSION, vol. 26, July 1956, pp. 559–564.

[3] Alvarez, L. W., et al., "The Catalysis of Nuclear Reactions by μ^- Mesons," Radiation Laboratory, University of California, Berkeley, Report UCLR-3620, Dec. 10, 1956.



The Deadly DART Strikes Home!

The fast and powerful Dart is a rocket propelled surface-to-surface missile designed for Army Ordnance by Aerophysics Development Corporation, a subsidiary of Curtiss-Wright.

The smokeless – solid propellant rocket motor was developed by Grand Central under sub-contracts from Aerophysics Development Corporation and Army Ordnance. The deadly Dart is one more application of dependable solid propellant rocket power by Grand Central.

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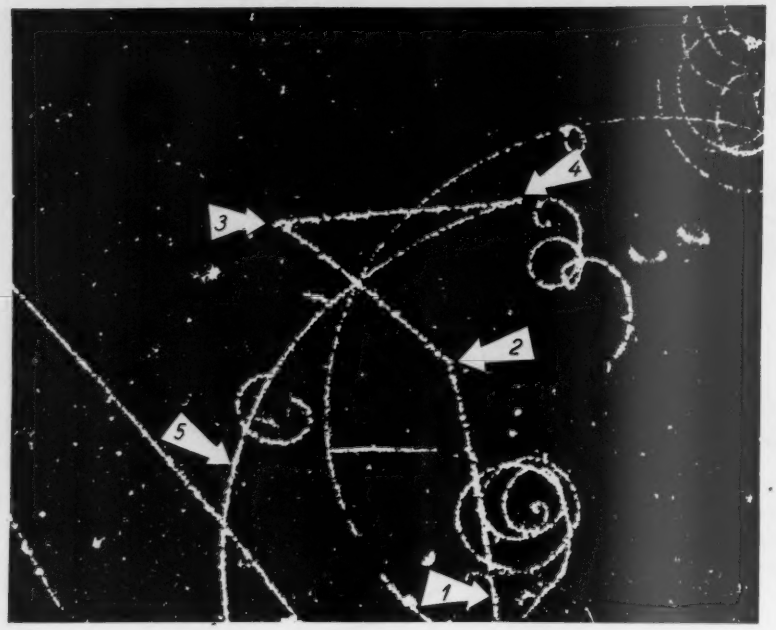


Catalysis of Nuclear Reactions by μ^- mesons. (1) μ^- meson enters bubble chamber, (2) catalyzes the reaction between a deuteron and a proton ($\mu^- + d + p \rightarrow He^3 + \mu^-$), (3) catalyzes yet one process and (4) decays into two neutrinos (not visible) and an electron ($\mu^- \rightarrow e^- + 2\nu$). (5) The electron is deflected by the magnetic field and leaves the chamber.

In a single case a μ^- meson was observed to catalyze two fusion processes (see figure). By increasing the concentration of deuterium in the bubble chamber this very important effect and similar ones may be investigated.

The μ^- meson is unfortunately too short-lived to make this very interesting process feasible for energy production. It is found that the reaction will be possible, when the ratio of the lifetime of the meson to the time of reaction is of the order of 10^5. It becomes marginal at a ratio of 10^3 to 10^2, while a ratio of 10 is prohibitive.

Fusion Powerplants

The construction and utilization of fusion powerplants on earth will not differ greatly from the present nuclear reactor stations. The reactants will be separated from sea water where the ratio of deuterium—one of the most promising fuels—to hydrogen is 1:7000. The energy available from fusion of deuterium is approximately 4×10^{10} Btu per pound of D_2 or, referred to water, 6.6×10^5 Btu/lb. This means that 1 lb of water can yield the same energy as 60 lb of coal, which has an average chemical energy of 0.11×10^5 Btu/lb.

The end products are hydrogen and tritium, which may be used for further fusion. The water from which the deuterium was separated offers a potential source for desalinated water, available for irrigation.

The fusion process has often been considered for propulsion purposes. Best known of these is Eugene Saenger's photon rocket, which is certainly most promising from the flight performance angle (see Table 2) but which is technically not feasible.

The more likely methods of using fusion processes for propulsion are the production of thrust by thermodynamic expansion of the hot reaction products, and the use of heat transfer systems for "conventional" propulsion, such as arc-heated or ionic rockets. Of these methods, the direct expansion of the reactants is the most efficient, but calls for more accurate control of the fusion process. A very high exhaust velocity can be expected, perhaps of the order of 10^8 fps. There is no need to expound upon the point that the almost insurmountable problem of cooling the chamber walls is aggravated in the nozzle area.

The heat transfer rocket will not be basically different from the present proposals for fission rockets. The fusion energy per weight unit is $1\frac{1}{3}$ times larger than fission energy. More important is the availability of hydrogen in the solar system, permitting refueling on other planets, while fissionable materials are less abundant and much more difficult to retrieve.

The catalyzed fusion process may be the answer to the propulsion problem. The most important factor is that the process can take place at almost any temperature. The process is not maintained by the enormous heat of the thermonuclear fusion, but simply by the catalyzing effect of a suitable negative particle fraction. As mentioned above, the particle has only a limited lifetime, during which it can substitute the electron of a reactant, producing a tight-packed mesic molecule. The possibilities of replenishing the catalyzing particle are manifold. Somewhere in the process a cycle may be fitted which has the catalyst among its reaction products, thereby introducing make-up catalyst in the reactor.

Fusion propulsion systems of the "hot" type will have low thrust-to-weight ratio, and will therefore be applicable only to space operations, such as transfer from a satellite orbit around the earth to one around Mars or Venus. "Cold" fusion systems offer unlimited possibilities.

Table 2 Flight performance of an imaginary photon rocket

Destination	Travel time for crew	True time on earth
Moon	3.5 hours	3.5 hours
Planets	2 days	2 days
α-Centauri	3.6 years	6 years
Center of galaxy	20 years	60,000 years
Andromeda galaxy	26 years	2,500,000 years
Round trip in galaxy	42 years	4 billion years

(Continued from page 568)

5052 puts out 27,000 lb for 4 sec and weighs about 1020 lb.

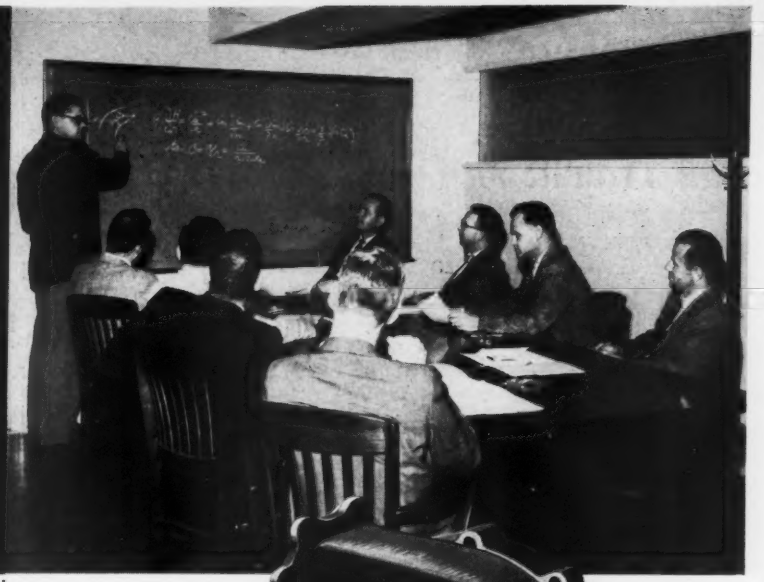
Korea: The Republic of South Korea has also asked for U. S.-made nuclear missiles since it feels that Red China-dominated North Korea is being armed with Soviet rockets.

RESEARCH AND DEVELOPMENT

• Frank D. Newbury, Assistant Secretary of Defense for research and engineering, resigned last month, climaxing a dispute arising out of claims by many scientific groups, including the Defense Dept.'s own science board, that Newbury, an engineer, had been putting too much stress on engineering and applied research, as opposed to basic research.

• A pulsejet engine from France has been installed in an English Cooper Mk. V auto. The intake faces rearward and is atop the exhaust nozzle. Nearby, the noise of the unit is said to be "inoffensive," but further away the sound is considerable.

Pump Problems ?



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ARS News

San Francisco Program Set

Eight Sessions, Trip to Ames Lab Features of June 10–13 Meeting

EIGHT technical sessions are slated for the ARS Semi-Annual Meeting to be held at the Hotel St. Francis in San Francisco, June 10–13. The meeting, held in conjunction with the ASME Semi-Annual Meeting at the Sheraton Palace Hotel in the same city, will also include a luncheon, a banquet and a field trip to the NACA Ames Aeronautical Laboratory at Moffett Field.

Antoni K. Oppenheim, president of the host Northern California Section, and meeting chairman, announces that exhibits of companies located in the regions of the Northern California and Sacramento Sections will be on display on June 11 and 12.

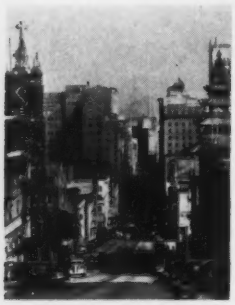
The Navy's top ballistic missile man, Rear Admiral W. F. Raborn, director of the Bureau of Ordnance's Special Projects Office, will be the principal speaker at the banquet on June 11.

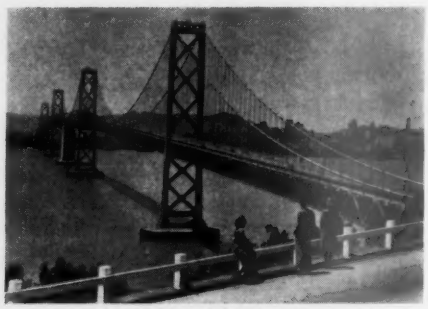
Dan A. Kimball, former Secretary of the Navy and now president of Aerojet-General Corp., Azusa, Calif., will be the principal speaker at a luncheon on the same day.

Smith De France, director of the Ames Laboratory, has indicated that an extremely interesting guided tour of the facility (see photo) will be offered on Thursday, June 13.

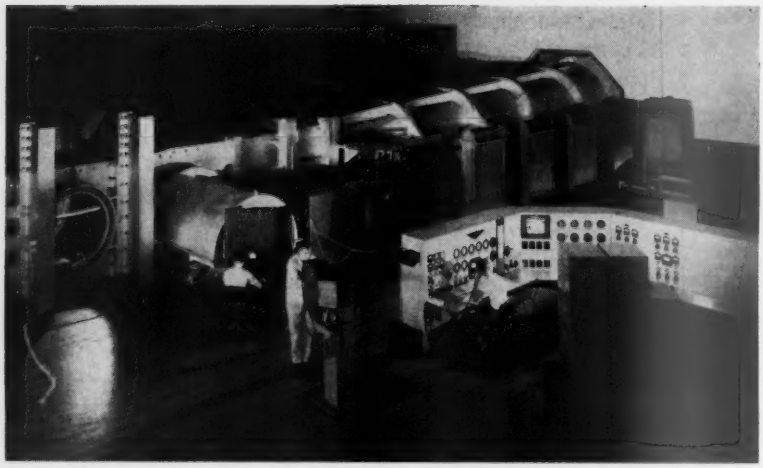
The complete program is given below.

A. K. Oppenheim, meeting chairman and president, Northern California Section.





Cable cars, Chinatown and the Bay Bridge, three of San Francisco's tourist features



Supersonic wind tunnel at Ames Lab will be one of items of interest on field trip.

SEMI-ANNUAL MEETING PROGRAM

MONDAY, JUNE 10

2:00 p.m. — **Mezzanine**

Registration Opens

TUESDAY, JUNE 11

8:00 a.m. — **Room 217**

Authors' Breakfast

9:30 a.m. — **Borgia Room**

Instrumentation and Guidance

Chairman: John J. Burke, Hallamore Electronics Co., Anaheim, Calif.
Vice-Chairman: D. Folland, Convair-Astronautics, San Diego, Calif.

✦ Elements of Inertial Navigation, by W. T. Russell, Ramo-Wooldridge Corp., Los Angeles, Calif. (431–57)

✦ Elements and Applications of Radio Guidance, by C. R. Gates, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, Calif. (432–57)

✦ The Bomarc Flight Vibration and Its Development into an Equipment Specification, by G. G. Setterlund, Boeing Airplane Co., Seattle, Wash. (433–57)

✦ Instrumentation for Rocket Engine Controls Research Testing, by J. D. Gillett. (434–57)

✦ Recent Advances in Dynamic Pressure Measurement Techniques, by F. F. Liu and T. W. Berwin, Rocketdyne, Canoga Park, Calif. (435–57)

9:30 a.m. — **Italian Room**

Liquid Rockets I

Chairman: R. Dillaway, Rocketdyne, Canoga Park, Calif.
Vice-Chairman: J. H. Beverage, Aerojet-General Corp., Azusa, Calif.

✦ Design of Cooled Jet Deflector Plates, by Paul J. Petrozzi, Aerojet-General Corp., Sacramento, Calif. (436-57)

✦ Exhaust Nozzle Contour for Optimum

Thrust, by G. V. R. Rao, Marquardt Aircraft Co., Van Nuys, Calif. (437-57)

✦ A Liquid Propellant Rocket for Group Training, by G. S. James and D. Starrett, Aerojet-General Corp., Sacramento. (438-57)

✦ Rocket Engine Thrust Vector Control, by William J. Brennan, Rocketdyne, Canoga Park, Calif. (439-57)

✦ Development of the CML-4N Rocket Engine, by R. C. Truax, Western Development Div., ARDC, Inglewood, Calif. (440-57)

12:00 p.m. **Colonial Room**

Luncheon

Toastmaster: Daniel Tenenbaum, president, Sacramento Section

Speaker: Dan A. Kimball, president, Aerojet-General Corp., Azusa, Calif.

2:30 p.m. **Borgia Room**

Solid Rockets

Chairman: Barnet R. Adelman, Ramo-Wooldridge Corp., Los Angeles, Calif.

Vice-Chairman: Howard H. Niederman, Atlantic Research Corp., Los Angeles.

✦ Development of ASP Rocket, by Robert Green, Grand Central Rocket Co., Redlands, Calif. (442-57)

✦ Solid Propellant Gas Generators for Auxiliary Power, by P. G. Butts and H. E. Perkins, Olin Mathieson Chemical Corp., East Alton, Ill. (443-57)

✦ Production Problems in Solid Propellants, by J. A. McBride, Phillips Petroleum Co., Bartlesvllle, Okla. (444-57)

✦ A Practical Mathematical Approach to Grain Design, by Max W. Stone, Rohm & Haas Co., Redstone Arsenal Research Div., Huntsville, Ala. (445-57)

2:30 p.m. **Colonial Room**

Combustion

Chairman: Martin Summerfield, Princeton University, Princeton, N. J.

Vice-Chairman: Walter Berl, Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Md.

✦ Influence of Pressure on the Combustion of Liquid Spheres, by George A. Agoston, Bernard J. Wood and Henry Wise, Stanford Research Institute, Menlo Park, Calif. (446-57)

✦ Flame Stabilization in the Boundary Layer of Heated Plates, by Richard W. Ziemer, Armour Research Foundation, Chicago, Ill., and Ali Bulent Cambel, Northwestern University, Evanston, Ill. (447-57)

✦ A Theory of Spray Combustion, by C. C. Miesse, Armour Research Foundation, Chicago, Ill. (448-57)

✦ Theory of Maximum Rates of Heat Release in Inhomogeneous Combustion Processes, by H. N. Powell, General Electric Company, Cincinnati, Ohio. (449-57)

7:00 p.m. **Colonial Room**

Semi-Annual Banquet

Toastmaster: Antoni K. Oppenheim, president, Northern California Section

Speaker: Rear Admiral W. F. Raborn, director, Special Projects Office, Bureau of Ordnance

WEDNESDAY, JUNE 12

8:00 a.m. **Room 217**

Authors' Breakfast

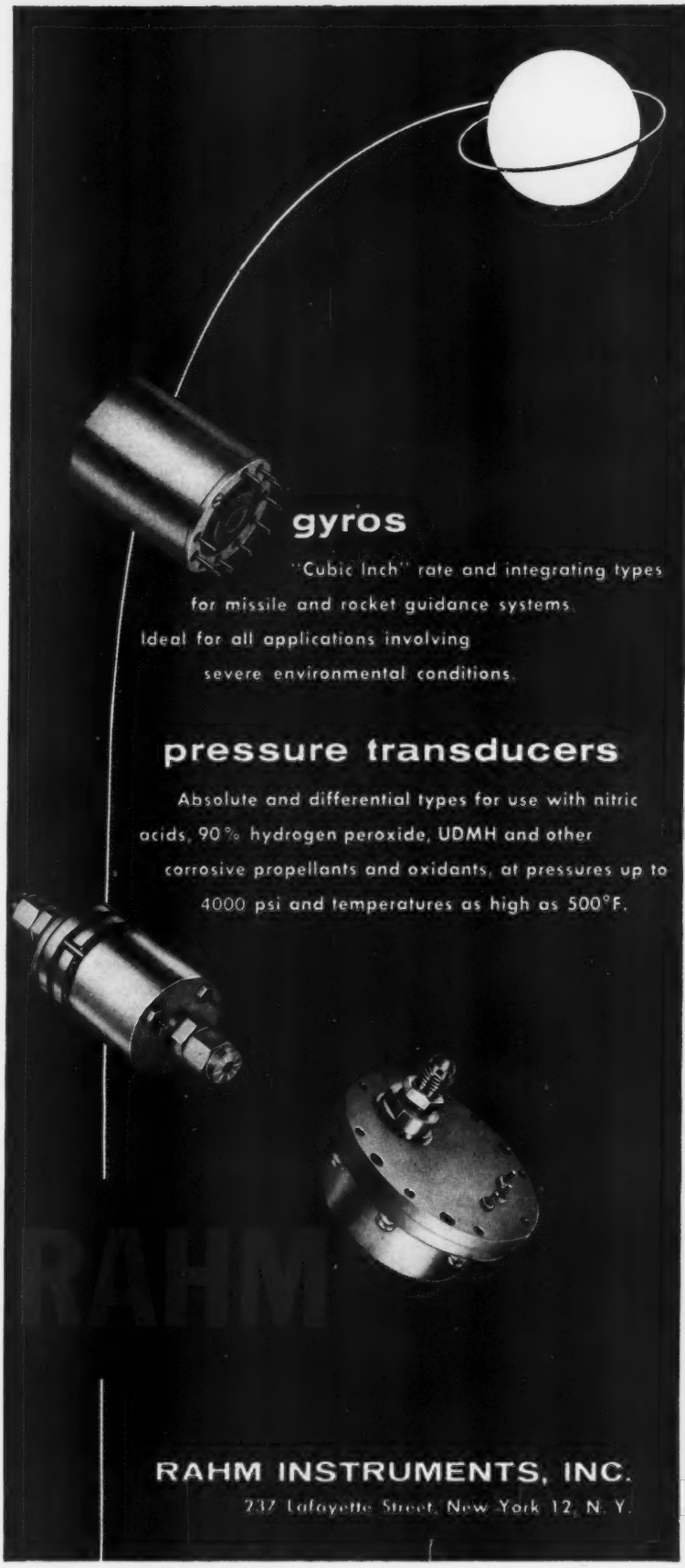
9:30 a.m. **Borgia Room**

Ramjets

Chairman: Brooks T. Morris, Marquardt Aircraft Co., Van Nuys, Calif.

Vice-Chairman: Robert J. Naegele, Lockheed Aircraft Corp., Missile Systems Div., Sunnyvale, Calif.

✦ Ramjet Test Facility Planning, by R. O. Dietz and A. H. Hinners, Aro, Inc., Arnold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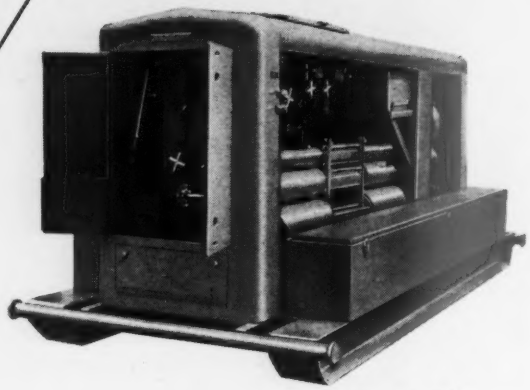

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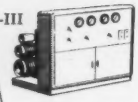

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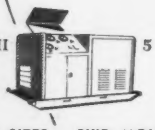

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Engineering Development Center, Tullahoma, Tenn. (450-57)

✦ Techniques of Flight Simulation for Ramjet Engines, by R. Greenberg, Wright Aeronautical Div. of Curtiss-Wright Corp., Wood-Ridge, N. J. (451-57)

✦ Testing Air Breathing Supersonic Powerplants, by G. A. Sears and J. J. Bajek, Marquardt Aircraft Co., Van Nuys, Calif. (452-57)

✦ Techniques, Facilities and Instrumentation for the Experimental Determination of Ramjet Dynamic Characteristics, by Carl B. Wentworth and George Vasu, NACA, Lewis Flight Propulsion Laboratory, Cleveland, Ohio. (453-57)

9:30 a.m. **Italian Room**

Hypervelocity Flight

Chairman: H. Julian Allen, NACA, Ames Aeronautical Laboratory, Moffett Field, Calif.

Vice-Chairman: S. A. Schaaf, University of California, Berkeley, Calif.

✦ Aerodynamics of Hypervelocity Flight, by Lester Lees, California Institute of Technology, Pasadena, Calif. (455-57)

✦ Performance of Long Range Hypervelocity Vehicles, by A. J. Eggers, Jr., NACA, Ames Aeronautical Lab., Moffett Field, Calif. (456-57)

✦ A Survey of Heat Transfer Problems Encountered by Hypersonic Aircraft, by Jackson R. Stalder, NACA, Ames Aeronautical Lab., Moffett Field, Calif. (457-57)

✦ Characteristics of the Upper Atmosphere Pertaining to Hypervelocity Flight, by C. Frederick Hansen, NACA, Ames Aeronautical Lab., Moffett Field, Calif. (458-57)

✦ Structural Problems of Hypervelocity Vehicles, by Samuel P. Batdorf, Lockheed Aircraft Corp., Missile Systems Div., Sunnyvale, Calif. (459-57)

10:00 a.m. **Room 221**

Directors Meeting

2:30 p.m. **Italian Room**

Space Flight

Chairman: H. F. Dunholter, Convair-Astronautics

Vice-Chairman: E. V. Laitone, University of California, Berkeley, Calif.

✦ Ground Simulation of Meteoritic Dust Impact on Space Vehicles, by D. H. Robey, Convair-Astronautics, San Diego. (465-57)

✦ Effect of Air Drag on Elliptic Satellite Orbits, by Robert E. Roberson, NAA Autonetics Div., Downey, Calif. (466-57)

✦ Cislunar Operations, by Krafft Ehricke, Convair-Astronautics, San Diego. (467-57)

2:30 p.m. **Borgia Room**

Liquid Rockets II

Chairman: Benjamin S. Mesick, Arthur D. Little, Inc., Los Angeles, Calif.

Vice-Chairman: James A. Broadston, Rocketdyne, Canoga Park, Calif.

✦ Problems Associated with Regenerative Cooling of Rocket Thrust Chambers, by Leo E. Dean and Lucian A. Shurley, Aerojet-General Corp., Sacramento, Calif. (460-57)

✦ Automatic Propellant Heat Transfer Data-Recording System, by Robert Ellison, Reaction Motors, Inc., Denville, N. J. (461-57)

✦ The Spreading of Supersonic Jets from Axially Symmetric Nozzles, by C. J. Wang and J. B. Peterson, Ramo Wooldridge Corp., Los Angeles, Calif. (462-57)

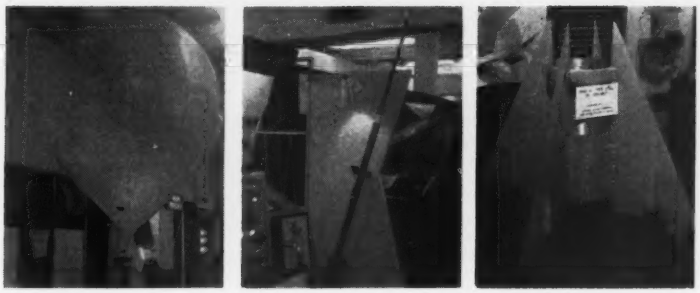
✦ The Application of High Speed Motion Pictures in Fuel Injection Studies, by Carl H. Builder and Gilbert S. Bahn, Marquardt Aircraft Co., Van Nuys, Calif. (463-57)

THURSDAY, JUNE 13

12:30 p.m. **Field Trip**

Field trip to NACA Ames Aeronautical Laboratory, Moffett Field, Calif.

ARS Spring Meeting Rings the Bell

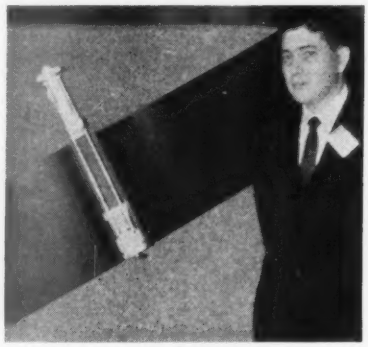


Among the highlights of the exhibit were (l to r) this scale-model Rockoon-balloon-rocket combination displayed by Winzen Research; Cooper Development Corp.'s Hasp; and tail assembly for Pogo-Hi developed by New Mexico A.&M.A. College.

A TOTAL of 1388 scientists, engineers and their guests registered at the AMERICAN ROCKET SOCIETY's national Spring Meeting early last month in Washington's Sheraton Park Hotel. They heard 34 papers and a number of talks Thursday through Saturday, April 4–6, and witnessed the Cherry Blossom pageantry after the sessions.

The enrollment was the largest ever at an ARS national gathering.

Complementing the ten technical sessions was a 75-booth exhibition by prime missile contractors, equipment manufacturers, the armed services and the National Advisory Committee for Aeronautics. Exhibitors reported very large attendance at the imaginative displays, which included some real rockets of the smaller sizes as well as scale models of bigger "birds."



M. I. Willinski, Rocketdyne, with model of ion-propelled "Snooper" vehicle.

One paper receiving a good deal of attention was "Project Snooper: A Program for Reconnaissance of the Solar System with Ion Propelled Vehicles" (419–57), by Martin I. Willinski and Mrs. Elsie C. Orr of North American's Rocketdyne. The information outlined was the culmination of a number of years of off-hours' exercise for the authors, who work in the preliminary design section.

"Snooper" vehicles, as described in the paper, would be unmanned, lightweight, nuclear-powered ion rockets weighing about 3300 lb. They would be lifted into an earth satellite orbit by a chemical propellant rocket, then set off under their own power. Once orbiting another planet, perhaps for as long as a year, the nuclear generator would provide a source of energy for $\frac{3}{4}$-ton of instruments and telemetering equipment.

Ion discharge velocities of 657,000 fps were cited, along with other details which caused the engineers to claim for such craft low cost and "simplicity and feasibility in terms of current technology." Private guesses by knowledgeable scientists mentioned spans of about eight years to achieve a "Snooper" if work began now.

Papers presented at the meeting were:

High Speed Sleds

✦ Supersonic Track Facilities at the Naval Ordnance Test Station, by B. R. Egbert and D. P. Ankeney, U. S. Naval Ordnance Test Station, China Lake, Calif. (392-57)

Problems of rocket-propelled carriage design, with emphasis primarily on importance of correct initial design study; structural criteria also covered, with the major design approach and criteria outlined.

✦ Design Considerations of Two Large Liquid Rocket Sled Pusher Vehicles, by H. Davies and D. S. Smith, Reaction Motors, Inc. (393-57)

The propulsion system of the transonic and supersonic RMI sleds is a solution to the need for variable thrust to maintain given velocities in large vehicles; design considerations of the system and vehicle are detailed.

✦ Aberdeen Proving Ground Ballistic Track, by Mitchell E. Bonnett and Benjamin F. Goodwin, Aberdeen Proving Ground. (396-57)

The 2500-ft track for evaluating rocket warhead and fuse functioning, plus free flight and other conditions, is covered in many aspects.

✦ Supersonic Rain Erosion Testing of Missile Radomes, by K. Barr, Experimental Track Branch, AFFTC, Edwards AFB, Calif., and E. J. Steeger, Thermodynamics Laboratory, Convair. (402-57)

This report presents discussions of design parameters, sled structure, operational performance and track problems encountered during 19 tests of the ability of plastic radomes and radome materials to withstand erosion from rainfall at Mach 2 and above.

✦ Design Determinants for the Holloman Horizontal Test Stand, by William T. Bateman, Holloman Air Development Center. (404-57)

Paper not available at press time.

✦ Track Testing at the Air Force Armament Center, by Richard K. Hendricks, Eglin AFB. (405-57)

Described is the 2000-ft track-type Damage Potential Launcher for engineering evaluations of weapons, including instrumentation, permanent support facilities and rocket-propelled test vehicle design.

✦ Precision Measurement of Supersonic Rocket Sled Velocity, by F. J. Beutler, Ramo-Wooldridge Corp., and L. L. Rauch, Professor of Instrumentation, Univ. of Michigan. (406-57)

The desired velocity accuracy and band width combination of a sled testing all-inertial guidance system components can be obtained, the authors say, by combining the data from an accelerometer with relatively infrequent track time and position data of practical accuracy. A method is proposed and detailed error analysis is presented.

✦ The Capabilities of the Holloman Track, by Gerhard R. Eber, Holloman Air Development Center. (407-57)

The seven-mile track, its intricacies of construction and limits are detailed.

✦ Some Remarks on the Design of High Speed Sled Test Vehicles, by Richard A. Hirsch, Aircraft Armaments, Inc. (408-57)

Design problems, including costs, are presented, along with the outline and specifications of a typical installation.

✦ The Closed Circuit High-Speed Test Track, by H. J. Barten, Chicago Midway Laboratories. (409-57)

The feasibility of a track with circular sections to slow down the sled gradually for reuse is discussed.

✦ Track Testing at the Air Force Flight Test Center, by Ross R. Seger, Experimental Track Branch, EAFB. (410-57)

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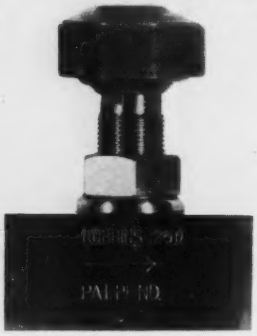

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Abstracts Due June 1

Abstracts for the ARS 12th Annual Meeting, Dec. 2–6, 1957, in New York, are due June 1. Complete manuscripts are due Aug. 1.

The sessions tent tively scheduled and the committee chairmen to whom abstracts should be sent, are:

Solid Rockets: W. L. Rogers, Aerojet-General Corp., Azusa, Calif.

Combustion: John F. Tormey, Rocketdyne, Research Section, Canoga Park, Calif.

Ramjets: Brooks T. Morris, Marquardt Aircraft Co., Engineering Div., Van Nuys, Calif.

Instrumentation and Guidance: J. J. Burke, Hallamore Electronics Co., 8352 Brookhurst, Anaheim, Calif.

Liquid Rockets: Col. E. N. Hall, ARDC, Western Development Div., Box 262, Inglewood, Calif.

Space Flight Symposium, Space Law and Sociology: Krafft A. Ehricke, Convair-Astronautics, San Diego, Calif.

Human Factors: Maj. David G. Simons, Space Biology Branch, Aero Medical Field Lab., Holloman AFB, N. M.

Test track development is traced and present AFFTC facilities, with expansion plans, reviewed.

✦ Sled Testing the Emergency Escape System: The Human Factor, by James F. Hegenwald, Jr., and Edward A. Murphy, Jr., North American Aviation, Inc. (411-57)

Physiological, mechanical and structural effects of ejection from high performance aircraft, including the effects on personal pilot gear, are reported.

✦ Development of RESCU Mark I, by Hugh F. Mohrlock, Jr., Convair. (414-57)

Escape from continually increasing flight performance envelopes are categorized and the features of the Mark I device discussed.

✦ Liquid Rockets for Supersonic Sleds, by C. E. Roth, Jr., and H. M. Poland, Aerojet-General Corp. (415-57)

Feasibility after static and dynamic testing of 4 to 6 g, 1500 to 1600 fps sleds is recommended after discussion.

✦ Measurements of the Vibration Environment in a Supersonic Liquid-Propellant Rocket Sled, by G. M. Barr and S. C. Morrison, Ramo-Wooldridge Corp. (416-57)

Measurements made at SNORT of vibration environment within the nose sections of two sleds, including methods of making the measurements, are detailed.

Space Sociology

✦ Some Current Considerations Affecting the Evolution of Space Law, by P. K. Roy, International Civil Aviation Organization. (388-57)

The fundamental question regarding who has jurisdiction over outer space and some correlaries are raised.

✦ Neuro-Endocrine Responses Essential for Survival in Space, by William R. Brewster, Jr., M.D., Patricia S. Osgood and James P. Isaacs, Harvey Medical School, Massachusetts General Hospital. (389-57)

Although the stresses to be imposed by space travel are not yet clearly defined, some insight may be gained by consideration of the fundamental physiological mechanisms that are known to be important. The authors review these mechanisms.

✦ Probable Influences of Satellites on Society, by N. E. Felt, Jr., The Martin Co. (691-57)

The primary thesis is that the satellite program can be used to educate the public to the value of basic scientific research.

✦ Space Law and Metalaw—Jurisdiction Defined, by Andrew G. Haley, general counsel, AMERICAN ROCKET SOCIETY. (397-57)

A review of the general idea of space law sovereignty and jurisdiction, including concepts for a demarcation of space and air, is presented.

✦ Space Flight and Our Technological Revolution, by Wernher von Braun. (698-57)

The culmination of the technological revolution, aimed at freeing man from physical labor, will be realized in space travel with the breaking of his final bond, gravity.

✦ Astronautics, Public Relations and the Press, by Erik Bergaust, American Aviation Publications, Inc. (399-57)

The importance of having an informed press is presented.

✦ The Function of Universities in Astronautical Research, by S. F. Singer, Physics Department, University of Maryland. (401-57)

Technical, as well as cultural and sociolegal aspects of astronautics, as areas in which universities can contribute, are outlined.

Propulsive Systems

✦ Factors Which Influence the Suitability of Liquid Propellants as Rocket Motor Regenerative Collants, by D. R. Bartz, Jet Propulsion Laboratory, California Institute of Technology. (417-57)

Methods of analytical and experimental determination of pertinent heat transfer characteristics of propellants are reviewed and data compared for insight into operating conditions.

✦ Rocket Impulse Spectrum, by M. Farber, Aerojet-General Corp. (418-57)

Performance characteristics of the range of propellants are detailed.

✦ Project Snooper. (419-57). See page 579.

✦ The Relations Between Mission and Propulsion System in Missiles, by James M. Carter, Carter Laboratories, Inc. (420-57)

Requirements of the missile's mission influence the propulsion system, it is pointed out, and possibilities for optimizing the requirements are suggested.

✦ Techniques Used in Ramjet Engine Speed Control, by H. J. Nelson and R. B. Farrar, Bendix Products Division-Missiles. (421-57)

Successful speed control methods and devices are described.

Astronautics

✦ Mechanical Aspects of the Vanguard Flight Control System, by F. Gordon Sholes, The Martin Co. (424-57)

A wide variety of mechanisms and their testing equipment is detailed.

✦ Support Requirements for the Vanguard Satellite Launching Vehicle, by Sears Williams, The Martin Co. (425-57)

Facilities, handling and servicing equipment, and test and checkout equipment are discussed.

✦ Army Support of Vanguard, and a Dynamic Display System for Presenting Satellite Tracking Information (two parts), by Lt. Col. C. M. Parkin, Jr., and Edward J. Madden, Fort Belvoir, Va. (426-57)

Various constructions by the Corps of Engineers are enumerated, and the central projection of a globe on a flat screen for presenting true course being followed by satellite is outlined.

✦ Design, Fabrication and Testing of the First Man-Made Satellite, by Robert C. Baumann, Naval Research Laboratory. (427-57)

Detailed information on the construction of the satellite is presented (see JET PROPULSION, April 1957, p. 444).

✦ Re-entry of Spherical Bodies into the Atmosphere at Very High Speeds, by Krafft A. Ehricke and Helen Pence, Convair-Astronautics. (428-57)

Spectrum of descent of a series of spheres for re-entry velocities from subcircular to parabolic and angles of descent from 0 to −10 deg is given.

✦ Satellite Launching Vehicle Trajectories, by J. W. Siry, Benjamin Lepson, R. H. Wilson, Jr., R. B. Snodgrass and John L. Hammersmith. (429-57)

✦ Flare Measurements from Rockets, by T. A. Chubb, H. Friedman, J. E. Kupperian, Jr., and J. C. Lindsay, Naval Research Laboratory. (430-57)

The rocket system employed for such measurements, plus other problems, are discussed.

This was the scene at the gala banquet which rang down the curtain on the ARS Spring Meeting in Washington, D. C., last month.

Snapped at the ARS Spring Meeting

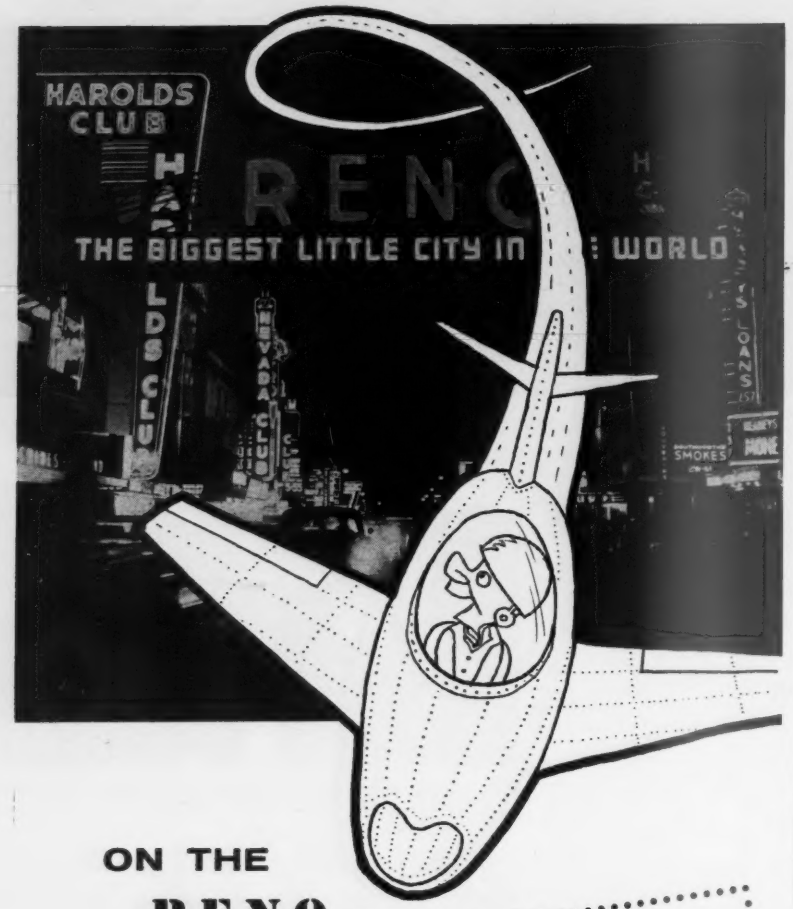
A. F. Spilhaus (left) and Rear Admiral Rawson Bennett (right) were presented with Fellow Memberships.

Alan T. Waterman (left) also received a Fellow Membership. Col. John T. Stapp (right) chairs first space sociology session.

Meeting Chairman Andrew G. Haley (right) goes over details with ARS President Robert C. Truax before banquet.

P. K. Roy (left) speaks at space sociology session. At right, Wernher von Braun and Theodore von Kármán listen closely.

Stopcock it in Reno



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Brooklyn Poly to Host ARS Student Conference

An ARS Eastern Regional Student Conference is being programmed for Dec. 6-7, 1957, under the auspices of the Polytechnic Institute of Brooklyn Chapter and the New York Section. The Conference comes immediately after the ARS 12th Annual Meeting, Dec. 2-6, in the same hotel, the Hotel Statler in New York.

T. Paul Torda of Poly, faculty adviser of the chapter, announces that the general theme of the conference will be the International Geophysical Year 1957-1958. Papers are invited on rockets, propulsion, astrophysics, instrumentation, upper atmospheric research, geophysics, guidance, cosmic rays, meteorology, satellites and other subjects related to the IGY program.

All applicants must be graduate or undergraduate students enrolled in an engineering or science course at an accredited university or college in Northeastern United States. Manuscripts should be prepared according to instructions shown in the "Preparation of Manuscripts" paragraph on the masthead page of JET PROPULSION (see p. 491). They should be submitted by Sept. 1, 1957, to:

Professor T. Paul Torda
ARS Eastern Regional Student Conference
Polytechnic Institute of Brooklyn
99 Livingston Street
Brooklyn 1, N. Y.

It is planned to publish a volume of the proceedings of the conference under sponsorship of the New York Section. All papers are automatically considered for the ARS-Chrysler Corp. Student Award and will be judged on the basis outlined for the award.

A luncheon during the conference will be addressed by a leading figure in the U. S. IGY program.

$1,000 ARS-Chrysler Corp. Student Award Offered

Decision has been made by the ARS Board of Directors to combine the Student Award with the ARS-Chrysler Corp. Award, announces Samuel K. Hoffman, Rocketdyne, chairman of the Awards Committee.

The new award, a grant of $1,000 toward the education of an undergraduate or graduate student, will be presented for the first time at the 1957 Annual Meeting in New York, and will be called the ARS-Chrysler Corp. Student Award. All travel and incidental expenses incurred in attending the Honors Night Banquet will be advanced to the winner.

Eligibility rules are as follows:

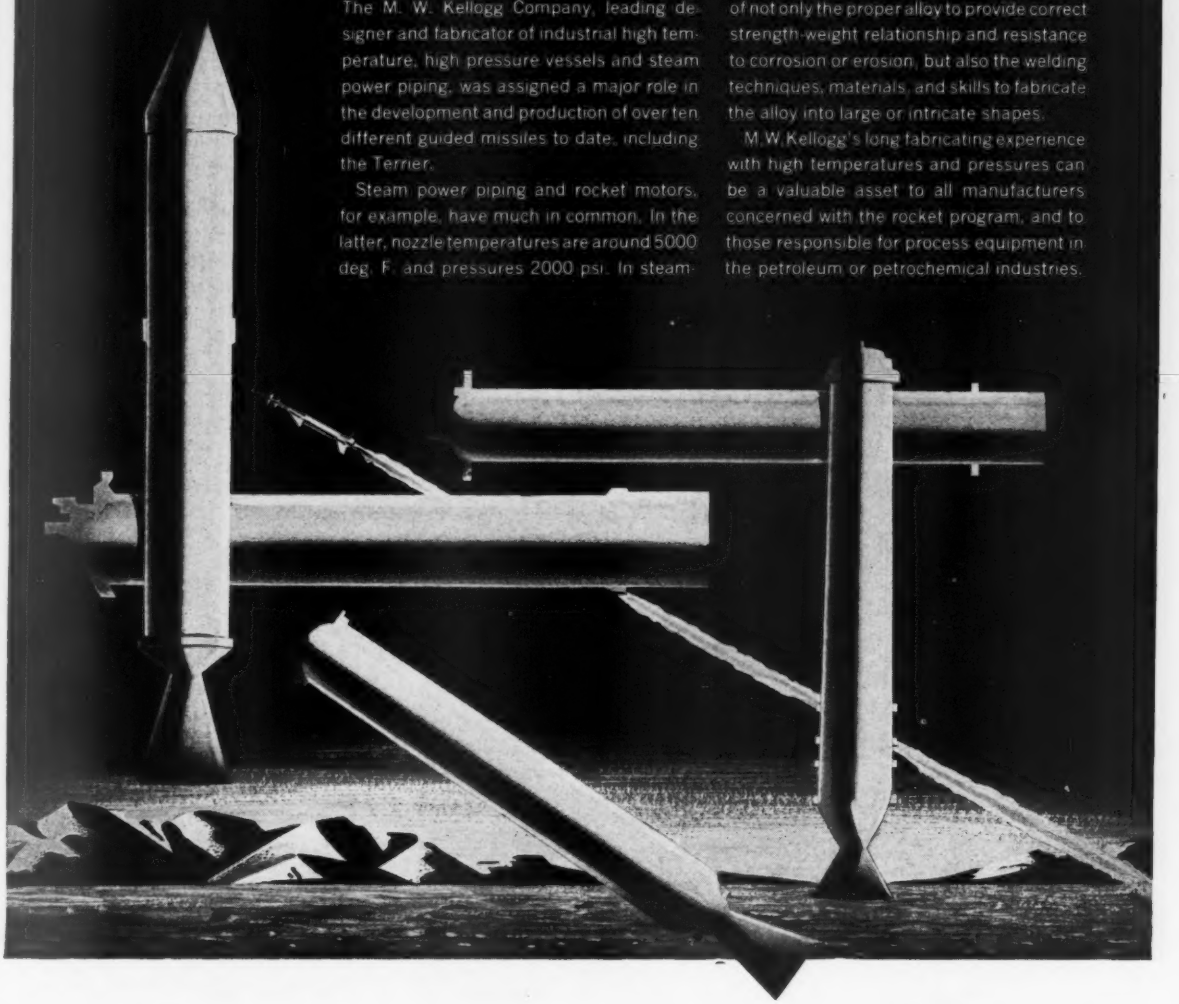
1 Applicants must be undergraduate

Outline of 1000 Temperature-Pressure Problems

Any rocket engine looks simple in silhouette—but its 150 or more parts present new and complex problems of operating temperatures and pressures. This is the reason why The M. W. Kellogg Company, leading designer and fabricator of industrial high temperature, high pressure vessels and steam power piping, was assigned a major role in the development and production of over ten different guided missiles to date, including the Terrier.

Steam power piping and rocket motors, for example, have much in common. In the latter, nozzle temperatures are around 5000 deg. F. and pressures 2000 psi. In steam-electric power plants, the Kellogg assignment concerns piping to withstand 1250 deg. F. and pressures over 5000 psi. Both problems include selection or development of not only the proper alloy to provide correct strength-weight relationship and resistance to corrosion or erosion, but also the welding techniques, materials, and skills to fabricate the alloy into large or intricate shapes.

M.W.Kellogg's long fabricating experience with high temperatures and pressures can be a valuable asset to all manufacturers concerned with the rocket program, and to those responsible for process equipment in the petroleum or petrochemical industries.



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or graduate students, above average in scholastic standing, enrolled in an engineering or science course of study at any accredited U. S. college or university.

2 Applicants must submit a technical paper treating a subject in the general field of rockets, jet propulsion or astronautics.

3 Manuscripts should be prepared according to instructions shown in the "Preparation of Manuscripts" paragraph on the masthead page of JET PROPULSION (p. 491).

4 Manuscripts should be submitted in duplicate, together with proof of scholastic standing in the upper half of applicant's class during the 1956-1957 academic year, by Oct. 1, to:

Chairman, Awards Committee
American Rocket Society
500 Fifth Avenue
New York 36, N. Y.

Papers will be judged on the basis of originality, content, method of presentation and clarity. All papers will become property of ARS, and their return to applicants cannot be guaranteed.

It is planned to invite the winning author to present his paper at the ARS Eastern Regional Student Conference, to be held after the Annual Meeting under the auspices of the Polytechnic Institute of Brooklyn Chapter.

ARS to Publish Second Monthly Magazine

The AMERICAN ROCKET SOCIETY will begin publication this summer of a second monthly magazine to be called ASTRONAUTICS, it was announced last month following a meeting of the Board of Directors in Washington, D.C.

Publication of a second magazine by the SOCIETY will permit much broader coverage of the rocket and guided missile field than has heretofore been possible. All ARS members will receive copies of both publications every month.

The new magazine will include articles in many fields in which members have expressed interest and will also provide detailed information about important technical developments and news events. It will also allow more complete coverage of the activities of the SOCIETY and its Sections throughout the country.

Research and development papers, along with related material and departments, will continue to appear in JET PROPULSION, along with several new features. Some of the departments now found in JET PROPULSION will be moved to the new publication.

Irwin Hersey, ARS Director of Publications, will be Editor of ASTRONAUTICS, while Martin Summerfield will be Editor of JET PROPULSION when the two-publication setup goes into effect.

National Program Committee Named

Announcement of the makeup of the 1957 ARS National Program Committee was made last month in Washington, D.C., by Kurt R. Stehling, Naval Research Laboratory, national program chairman.

Appointed to the committee are Antoni K. Oppenheim, University of California, president of the Northern California Section; Ali Bulent Cambel, Northwestern University; John Fenn, Princeton University; and Robert A. Gross, Fairchild Engine and Airplane Corp., president of the New York Section.

Human Factors Technical Division Established

The ARS Board of Directors has announced the formation of a new Human Factors Technical Division which will cover human activities and sciences such as space medicine and human engineering. Maj. David G. Simons, chief, Space Biology Branch,

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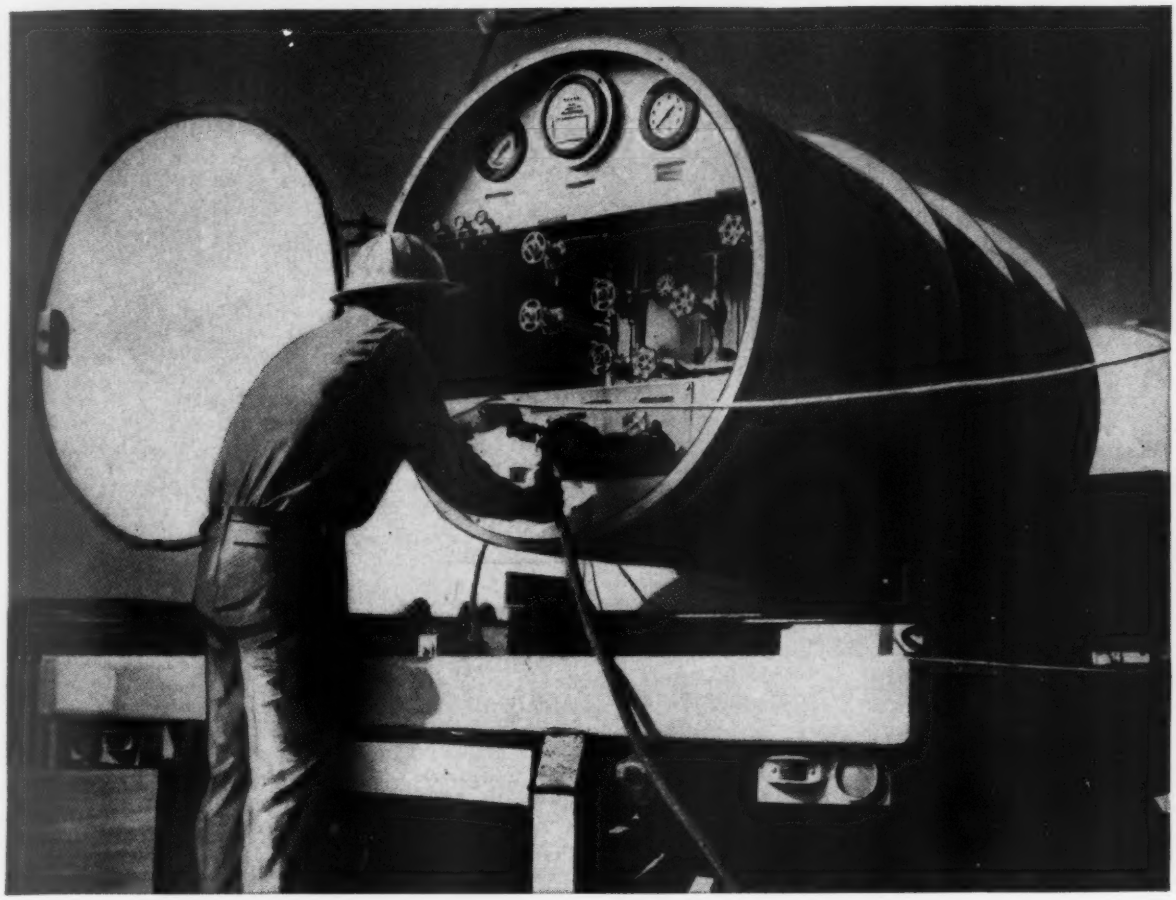

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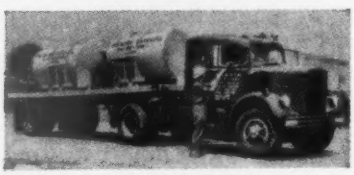

As a result of General Chemical research, fluorine can now be stored, transported and handled directly *as a liquid in tank-truck tonnages.* Large quantities can be used with far greater economy, simplicity and safety than has ever been possible with the normally gaseous form.

If your production or research program involves fluorine or fluorine-supplying chemicals, look into General's liquid fluorine development without delay. It makes possible new approaches to your problems that were impossible before. As a first step, write today for our comprehensive new technical bulletin, "Fluorine." It contains a wealth of helpful data.

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Basic Chemicals for American Industry

Aero Medical Field Laboratory, Holloman AFB, will be chairman of the committee heading up the division. This brings the number of ARS Technical Divisions to seven.

Like the other divisions, the Human Factors Division will plan sessions at national meetings, develop membership in the areas it covers, advise the Director of Publications on technical matters, assist in the nomination of candidates for awards and fellowships, sponsor technical reports or special publications, and provide technical representation for the ARS in cooperative efforts with other organizations.

Technical Division Membership Tallied

A tally of 3750 roster forms received by National Headquarters to date indicates membership in ARS Technical Divisions to be as follows:

Space Flight, 1880; Liquid Rocket, 1327; Instrumentation and Guidance, 1006; Propellants and Combustion, 859; Solid Rocket, 580; and Ramjet, 357.

The disparity between the number of forms tallied and total of the division tallies stems from the fact that members are permitted to enroll in two divisions.

Get 'em Young, Train 'em Right

The St. Joseph Valley Section believes in going after future missile and rocket engineers early, as indicated by this photo of the group's exhibit at the recent city-wide "Career Guidance Day" in South Bend. The exhibit, which included a 500-lb-thrust rocket engine, attracted a good deal of attention.

Sections

Alabama: H. W. Ritchey, Redstone Div., Thiokol Chemical Corp., recently gave a progress report on solid propellant rocket engine development before 300 members and guests of the Alabama Section at Huntsville. Among the subjects covered by Dr. Ritchey were recent developments in solid propellants, engine components and thrust control systems. He also presented preliminary calculations on a solid propellant rocket system for propelling a 1-lb payload to the moon.

Central Colorado: Approximately 300 members and guests heard Leonard Arnowitz, assistant project engineer for Project Vanguard, The Martin Co., discuss the earth satellite program at a joint meeting of the Central Colorado Section with the Denver chapter of the Institute of Aeronautical Sciences. Mr. Arnowitz augmented his presentation with slides and the Martin movie, "Horizon Unlimited."

At the previous meeting, Robert Waldo, Aerojet-General Corp., spoke on "New Ideas in High Altitude Sounding Rockets."

Central Texas: Richard C. Lea, Martin Co., Denver, was the guest speaker at a recent meeting of the Central Texas Section attended by over 50 members and guests. Mr. Lea's topic was the Viking, and his talk dealt primarily with the structural requirements of the rocket and troubles encountered in balancing loads under static and dynamic conditions.

Columbus: Abbott A. Putnam, Battelle Memorial Institute, has been elected president of the Section for 1957. Other new officers are Loren Bollinger, Ohio State University, vice-president; A. M. Greshemer Jr., North American Aviation, corresponding secretary; James L. Harp, Battelle, recording secretary; and D. E. Hall Jr., North American, treasurer.

Geoffrey Keller, director of the Perkins Observatory, was the featured speaker at the March meeting, held at the observatory and attended by over 100 members and guests—a new record. Dr. Keller discussed the size and orbits of bodies in our solar system and cosmic dust. While the

Head Central Colorado Section

Officers and board members of the Central Colorado Section, posed with the section charter, are (l to r): S. A. Johnson, Jr., Denver Research Institute, board member; George P. Townsend, Sundstrand Aviation Co., vice-president; John R. Youngquist, Denver Div.; Martin Co., president; Richard C. Lea, Denver Div., Martin Co., secretary; and J. L. Burridge, Denver Div., Martin Co., board member.

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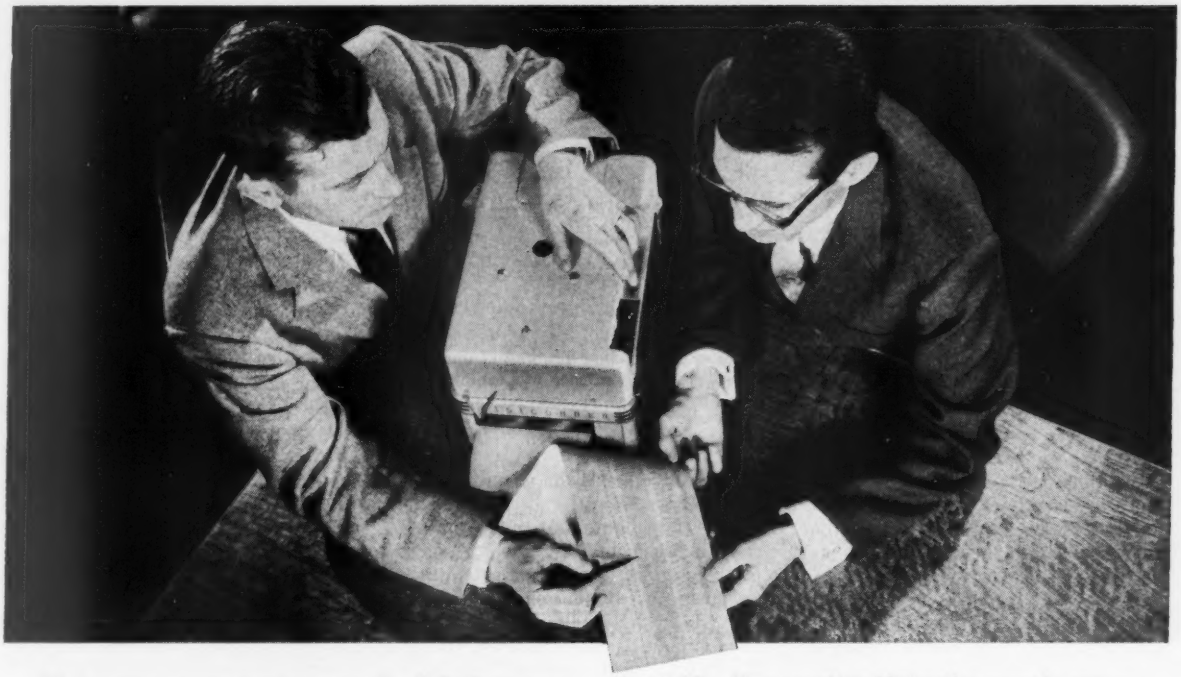

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Eye on the Sky

While poor weather conditions kept the Columbus Section from peeking at the heavens through this 69-in. reflecting telescope at the Perkins Observatory during a recent visit, its operation was explained in detail to 100 members and guests.

69-in. reflecting telescope at the observatory could not be used because of unfavorable weather, its operation was explained to the group.

Holloman: W. D. Stinnett, Vanguard project engineer at Aerojet-General Corp., was the guest of honor and principal speaker at the third of the special series of meetings of the Section devoted to astronautics. Speaking on "The Vanguard Vehicle and the Earth Satellite," Mr. Stinnett described some of the manufacturing techniques involved in building the Vanguard second stage and the problem of actual operation and tracking of the vehicle.

New York: Harold W. Ritchey of Thiokol Chemical Corp. was the featured speaker at the April meeting of the New York Section. Dr. Ritchey's topic was "Capabilities of Solid Rockets," and his discussion covered present and future propulsion capabilities of solid rockets as compared with liquid rockets, and the possible application of solid rockets to space flight vehicles. Films of actual flight tests were used to highlight the address.

Niagara Frontier: William A. Boles, director of public relations, Bell Aircraft Corp., was the featured speaker at the April meeting. Mr. Boles told how public relations works and how it fits into the corporate operations of a defense industry.

At the previous meeting, T. F. Reinhardt, research manager, Rocket Div., Bell Aircraft, discussed high energy propellants and their applications in the fields of guided missiles, military aircraft and earth satellites.

Newly elected officers of the Section are: Harry A. Ferullo, president; R. D. Reinhardt, vice-president; H. P. Heubusch, corresponding secretary; and Clayton Williams, treasurer.

Northern California: Some 60 members and guests of the Section enjoyed a showing of a sound film on "Stellar Evolution," featuring George Gamow, at the Section's last meeting in Millbrae, Calif. Section President A. K. Oppenheim announced at the meeting that future meeting notices would be included in a new section publication, "The San Francisco Engineer," which would be distributed to all members.

North Texas: A group of Convair engineers, all members of the Section, recently told Air Force Reservists that space flight has graduated from a "crackpot" idea to the realm of possibility. Speaking at a panel discussion at the Air Reserve Armory on "The Impact of Missiles on National Defense," John Kerr, Charles Crabtree, Lynn Lightbown and John Keller traced rocket progress through the years. Films of the Convair B-58 were also shown.

Sacramento: About 60 members and guests of the Sacramento Section heard Wayne Stinnett and John Altseimer, Aerojet-General Corp., and Arthur Leonard, member of the National Advisory Committee for the Tracking of Satellites, discuss Project Vanguard at a recent meeting. Mr. Altseimer opened the program with a review of the history and objectives of the Vanguard effort. Then Mr. Stinnett explained the operation of the three Vanguard stages, their performances and trajectories, and the problems to be overcome. Finally, Prof. Leonard explained satellite tracking procedures and the difficulties involved.

San Diego: Abe Berlad, senior staff scientist, Convair Scientific Research Laboratory, was the featured speaker at a joint meeting of the San Diego Section and the local IAS chapter. Dr. Berlad's topic was "Combustion Problems—Basic and Applied," and his discussion covered recent advances in the field and pointed up areas where further research and experimentation is necessary.

St. Joseph Valley: To stimulate interest among high school and junior high school students in the rocket and guided missile field, the Section recently participated in the first city-wide South Bend "Career Conference Day" exhibit. The Section displayed a 500-lb-thrust liquid rocket engine, along with posters and explanatory information. The exhibit attracted a good deal of attention.

H. H. Kurzweg, chief, Aeroballistic Research Dept., Naval Ordnance Laboratory, was the featured speaker at the last Section meeting. Approximately 125 people attended the meeting. Dr. Kurzweg appeared earlier on the South Bend, Ind., television network.

St. Louis: R. A. Cooley, Propellex Chemical Corp., newly elected president of the Section, discussed solid propellants, propellant performance characteristics, and present and future applications at a recent meeting. Other new officers are C. James Barr, Olin-Mathieson Chemical Corp., and C. E. Durham, White-Rodgers Electric Co., vice-presidents; Joseph A. Volk, Greenleaf Mfg. Co., treasurer; and P. W. Godfrey, McDonnell Aircraft Corp., secretary.

ARS Meetings Calendar

June 10–13: ARS Semi-Annual Meeting, Hotel St. Francis, San Francisco.
Aug. 25–28: ARS-Northwestern Technological Institute Gas Dynamics Symposium, Northwestern University, Evanston, Ill.
Dec. 2–6: ARS Annual Meeting, New York.

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Prefer ME or AE degree and a minimum of 6 years' experience in aircraft engines or airframes. You should have extensive design experience, including plenty of board time, shop contact, structural design, stress analysis. You will be working directly with design engineers and layout draftsmen on design of light weight, complex structures.

2. INSTRUMENTATION ENGINEER

BS minimum in mechanical, aeronautical or electrical engineering; 3–5 years' experience on aircraft engines. Must be familiar with the application of instrumentation to testing of rocket or other aircraft engines, the utilization of currently available instrumentation, or the modification and adaptation of such instrumentation for particular requirements and wide limits of flow temperatures, pressure, thrust, etc.

3. STRESS ENGINEER

Degree in engineering or applied mechanics. Required experience in mechanical design with emphasis on stress analysis: 3 years for an engineer, to 6 years for the senior engineer. Must be able to handle and/or supervise involved analysis—including the effects of dynamic forces, high temperature gradients and high pressure differentials—under conditions where light weight is vital.

4. PRODUCT ENGINEER

B.S. in M.E., A.E. or equivalent with a minimum of 5 years' airframe powerplant experience. Your background should also include engineering and customer contact on technical products and services. You will assume responsibility for organizing a program to apply new and existing powerplants to all types of missiles. 2–3 days of your week will be spent answering inquires and preparing proposals, 2–3 days traveling.

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People in the News

APPOINTMENTS

• **Lt. Col. John P. Stapp,** chief, Aero Medical Field Laboratory, Holloman AFB, has been promoted to Colonel. Col. Stapp's date of rank is April 8, 1957.

• **J. C. Clark** has been named staff assistant to J. R. Dempsey, manager of Convair-Astronautics, and will work on research and development of the Atlas Intercontinental Ballistic Missile. Dr. Clark was formerly associate leader of the Test Div., Los Alamos Scientific Laboratory.

• Aerojet-General Corp. has appointed **Alfred Schaff Jr.** manager of test and field service of the solid rocket plant, and **R. W. Powell** assistant division manager of the Avionics Div. **B. J. Gastineau** will succeed Powell as chief engineer, Avionics Div.

• **Milton E. Chandler,** co-founder of Chandler-Evans, now a division of Pratt and Whitney Co., Inc., has retired from active duty as engineering manager for Chandler-Evans, a post he has had for 20 years. He will continue to serve the company in an advisory capacity.

Craigie Ridenour

• **Lt. Gen. Laurence C. Craigie,** former commander of the Allied Air Force in Southern Europe, has joined American Machine and Foundry Co. as assistant to the defense products group executive, in charge of long range planning. Gen. Craigie is a director of Giannini Instrument Co. and Hydro-Aire Co.

• Lockheed Aircraft Co. has made **Louis N. Ridenour** the first director of its newly organized research and development branch. In two major appointments in the Missile Systems Div., **Willis M. Hawkins,** former director of engineering, has been named assistant manager of the division, and **William D. Snow** product planning branch chief.

• **Lt. Comdr. Enoch D. Blackwell,** assistant Bureau of Aeronautics representative for U. S. Navy at Buffalo, has joined the contract administration staff of the high energy fuels organization of Olin Mathieson Chemical Corp.

Hawkins Snow

• **Sherman M. Fairchild,** founder and board chairman of Fairchild Camera and Instrument Corp., has been elected president, succeeding John H. Clough, a past president of Fairchild Engine and Airplane Co. as well as president and director of Fairchild Camera and Instrument Co. Mr. Clough will be a consultant for the company.

• **Frank R. Carver** has been appointed radar development department chief; **E. E. Herman,** radar systems department chief; and **John C. Bailey,** head of the scientific and general recruitment for the systems development laboratories of Hughes Aircraft Co. Mr. Carver and Mr. Herman were previously associate heads of the radar department.

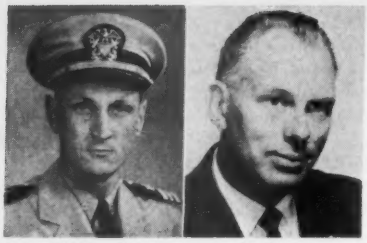
• Axelson Aviation, newly organized as a separate facility of Axelson Mfg. Co., has appointed **Robert R. Cole** chief design engineer. He was previously with Douglas Aircraft Corp.

• **Albert B. Deyarmond** has been named a member of the technical staff of the synthesis section of the tech-

Herman Carver

nical military planning operation, General Electric Co. Prior to this he was chief of preliminary design and chief of missiles projects at Ryan Aeronautical Co.

• **Richard W. Hodgson,** former vice-president in charge of engineering, has



Blackwell Bailey

been elected executive vice-president and director of research, and **Walter Y. Fish** has been elected vice-president in charge of engineering of Arnoux Corp. Prior to joining Arnoux one and a half years ago, Mr. Fish was in charge of Convair Florida missile test operations, Patrick AFB.

• **Alexander J. Yorgiadis** will be production manager and chief engineer

Cole Yorgiadis

and **A. Umit. Kutsay** assistant chief engineer of the new dynamics products group, Electronics and Instrumentation Div., Baldwin-Lima-Hamilton Corp.

• **Joseph Philipson** will head Atlantic Research Corp.'s new western division with headquarters in Pasadena.

Kutsay Philipson

The division will be particularly concerned with rocket, solid propellant and ordnance development. **Howard Niederman,** formerly of Aerojet-General, and **J. Russell McGibbeny,** previously with U.S. Flare Corp. and Associates, will hold key posts in the division.

• **Thomas F. Fitzgibbon,** Parker Aircraft Co., has been named manager of the Hydraulic Div. He aided in the establishment of the division in 1953 as divisional chief engineer.

• **Charles A. Nuebling** has been ap-

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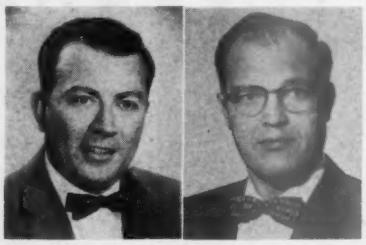
pointed manager of engineering, Electronics Div., Fairchild Controls Corp., a subsidiary of Fairchild Camera and Instrument Corp. Before joining Fairchild, he was director of electronics at Arma Div., American Bosch Arma Corp.



Douglas **Van Der Werff**

• **Louis C. Prisco** has been appointed sales engineering manager of the Reconnaissance Systems Div., Fairchild Camera and Instrument Corp. Previously he was sales manager of the division's nuclear instrumentation department.

• Bell Aircraft Co. has named **Robert M. Hawley** to the new position of director of sales and customer relations for the Weapon Systems Div. He was previously with Avro (Canada).

• **R. E. Day** has been appointed chief project engineer-metal products, Solar Aircraft Co. He was previously engineer for other Solar development programs.

• **Everett J. Long** and **James C. Kyle** will fill two newly created positions at the Transducer Div., Consolidated Electrodynamics Corp. Long will be assistant director of the division while Kyle will be assistant director for engineering. **Herbert A. Johnson,** assistant production manager, will move up to fill Long's previous position as production manager of the division.

• Finn Aeronautical Div., T. R. Finn Co., has named **Thomas L. Douglas** senior sales engineer. Prior to joining Finn, Mr. Douglas was plant manager of Tolan Machinery Co.

• Gladden Aircraft Products Corp., a subsidiary of Gladden Products Corp., has appointed **J. B. Van Der Werff** chief engineer.

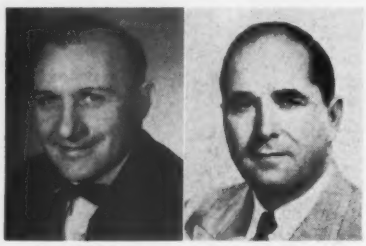
• **Irwin A. Davis** of Wyandotte Chemical Corp. will be project engineer of the company's new oxide products plant.

• **Clare E. Barkalow** has been named associate manager, Advanced Engineering Div., Lear, Inc.

• Ford Instrument Co., a division of Sperry Rand Corp., has announced several changes in personnel. **Robert J. Seymour** has been named manager of product planning while continuing as administrative assistant to the vice-president. **Edmund C. Bennett,** former assistant manager of the test and service department, has been appointed manager of the production test department in the Quality Control Div., while **Raymond R. Nadroga** has been appointed chief tool engineer.

• **John W. Ballentine** has been appointed aircraft field representative in the Los Angeles area for L. O. F. Glass Fibers Co. He was formerly an aerodynamics engineer with Douglas Aircraft Co.

• **Kenneth P. Bowen** has been named general manager, Summers Gyroscope Co. Previously, he was vice-president, manufacturing and material, Northrop Aircraft, Inc.



Barkalow **Bowen**

• **Jay J. Newman** has been appointed manager, new product and market development, RCA Components Div., after six years with RCA.

HONORS

• **William C. Foster,** vice-president in charge of high energy fuels activities, Olin Mathieson Chemical Corp., has been awarded an honorary Doctor of Laws degree by Syracuse University.

• **C. C. Ross,** manager, Liquid Engine Div., Aerojet-General Corp., and two other Aerojet officials, **Y. G. Lee,** director of research and planning, Liquid Engine Div., and **A. W. Cobb,** assistant senior engineer, have been appointed to special technical committees of the National Advisory Committee for Aeronautics for 1957. Mr. Ross, winner of the AMERICAN ROCKET SOCIETY'S 1956 Goddard Award, has been reappointed chairman of the subcommittee on rocket engines and named to the Committee on Power Plants for Aircraft. Mr. Lee has been appointed to the NACA subcommittee on combustion, and Mr Cobb to the subcommittee on aircraft noise.

• **Charles E. Wilson,** former president of General Electric Co., has been named chairman of the Manhattan College Council on Engineering Affairs.

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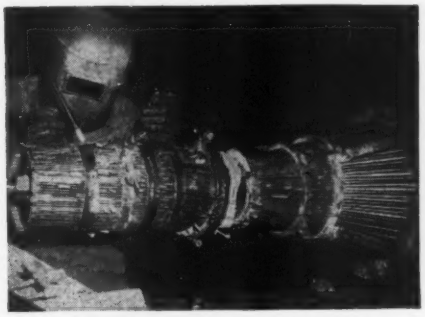

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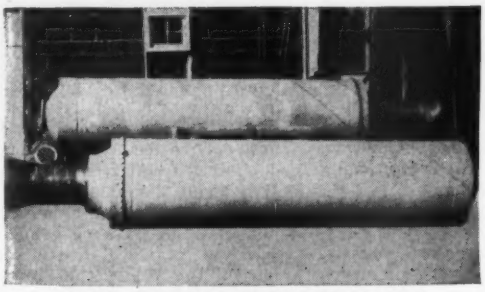

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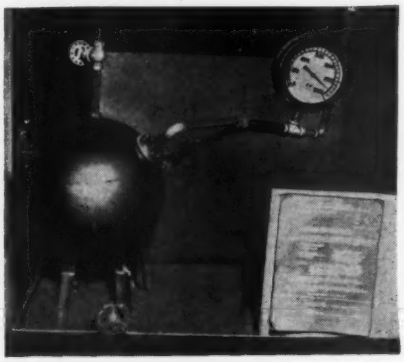

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Book Reviews

Ali Bulent Cambel, Northwestern University, *Associate Editor*

Die Wege des Strahlfluges (Trends in Jet Propulsion), by Eugen Sänger, R. Oldenbourg, Munich, June 1955, 14 pp. DM.

Reviewed by J. KESTIN
Brown University

The present brochure is the third to appear in a series sponsored by the German Forschungsinstitut fuer Physik der Strahlantriebe, e. V. (Research Institute for the Physics of Jet Propulsion, Inc.) in Stuttgart. It contains the text of a lecture delivered by the Institute's co-director, Dr.-Ing. Eugen Sänger who is well known internationally for his pioneering work in this field. It was, what one might term a "key-note" speech, and was read at the first meeting of the members of the Institute on July 12, 1955. It contains a review of present trends in the development of propulsion systems for aircraft, guided missiles and rockets, and attempts to assess their relative merits and regions of applicability. It is, necessarily, somewhat hurried, and even to a certain extent superficial, it being evident that the author tried to enclose a large amount of subject matter in the space of a short lecture. It contains a fairly complete listing of declassified information on American missiles and pilotless aircraft, indicating even the agency sponsoring each respective project and the manufacturer primarily responsible for its development.

The author tries to take a long view of developments, and attempts to predict likely trends. His enthusiasm is evident in every word he says, and he is undaunted by obvious practical difficulties which have to be overcome before space flight can be seriously considered to be a technical possibility, or before photon rockets and flight at speeds comparable, or even surpassing (*sic!*) that of *light* can become matters of practical engineering concern.

Soviet Air Power, by Richard E. Stockwell, Pageant Press, New York, 1956, xii + 238 pp. and Appendix. $7.50.

Reviewed by LEON TRILLING
Massachusetts Institute of Technology

"Soviet Air Power" is a detailed discussion of the history of the Soviet air force and a description of some of the air weapons now available to it. It also includes a discussion of some of the engineering philosophy and principles which underlie Soviet aeronautical engineering.

Because of our vast ignorance of the subject, a study with these aims fills a great need and is a great challenge. Unfortunately this challenge is only partly met in this book.

In fact, one may find a large number of errors in it, ranging from fairly trivial ones (on page 5 TsAGI is described as a training academy while it is in fact the Soviet equivalent of the NACA, its main purpose being research and testing rather than serving as an institution of higher learning; on page 39, Professor Gunther Bock is called Erwin von Bock; on page 47 there is an abstract of an article which purports to describe the design and flight testing of the MIG 15 and which is fairly clearly a fake) to important omissions.

A considerably more serious criticism seems to this reviewer to be the exaggerated emphasis put by Mr. Stockwell on the contributions of German technicians to the Soviet air development program. Clearly, much of the first-hand information in the book came from German scientists repatriated from the USSR who may have exaggerated the importance of their contributions. In fact an analysis of unclassified Soviet publications on fluid mechanics and the theory of elasticity and plasticity indicates that the Soviet air program pointing toward the development of weapons with supersonic capabilities was decided upon before 1942 and it was stated to this reviewer that while German contributions were significant in guidance and propulsion, they were negligible in aerodynamics and aircraft structures.

This comment leads to what this reviewer considers the most serious shortcoming of "Soviet Air Power," namely, the complete absence of any discussion of the Soviet research and development program which must be understood in order to permit the formulation of any plausible prediction of the rate of progress of Soviet airpower development.

"Soviet Air Power" is a snapshot intensely interesting and valuble in spite of its inaccuracies of the present state of Soviet air power development; there is now enough available material to give more depth to the picture by sketching in the engineering and scientific base on which Soviet air technology is built.

Introduction to Numerical Analysis, F. B. Hildebrand, McGraw-Hill, New York, 1956, 522 pp. $8.50.

Received by H. N. MCMANUS, Jr.,
Northwestern University

The intention of the author has been to prepare a text for a first course in numerical analysis which would provide the reader with a basic knowledge of the fundamental techniques of this field. As a consequence, a major part (five chapters) is devoted to the basic processes of interpolation, finite difference operations, numerical integration, and numerical differentiation. Each of these general topics is considered in some detail and special techniques which facilitate certain type calculations have been presented.

The balance of the volume is concerned with polynomial approximations by least squares, various methods of quadrature, nonpolynomial approximations, numerical solution of ordinary differential equations, and numerical solution of equations. This last topic is essentially an independent entity, as the methods involved are not based upon the remainder of the volume. Throughout the entire work consideration is given to the error introduced by the various techniques of approximation. Error propagation as a result of faulty data is also considered. The continuing attention to error throughout the volume serves to emphasize for the student the fact that the methods under study are indeed approximate rather than exact. Each chapter is liberally supplied with problems. An extensive bibliography is included.

It is quite obvious from the above that the emphasis is on theory rather than application. The chapter dealing with solution of differential equations is more a demonstration of numerical techniques than an application in the engineering sense. While this may appear undesirable to the engineer with a problem, it should be recognized that the field of numerical analysis is one which has been in the throes of rapid expansion. Consequently, many of the individuals who have entered the field have done so without formal training in the fundamentals. It is highly desirable that in the future personnel with a firm grounding in basic numerical processes be available to insure the continued extension of usefulness of this field. The present volume will serve an important function as a text for students interested in numerical methods, and those who have entered the field informally will find it valuable for independent study.

Guidance, by Arthur S. Locke and contributing authors from the Naval Research Laboratory, D. van Nostrand Co., New York, 16 index pp. + xvii + 713 pp. $12.50.

Reviewed by WALTER T. WHITE and
G. K. SLAUGHTER
Sperry Gyroscope Co.

This book is a compilation and brief treatise of the fundamental sciences and techniques that go into the design of a guided missile system. The principal author, A. S. Locke, a former consultant of the Radar Division, Naval Research Laboratory, has been ably assisted by scientists and engineers, each a specialist in his field, associated with the Naval Research Laboratory. "Guidance" is the first of a series of five volumes on "Principles of Guided Missile Design." The editor of the series is Capt. Grayson Merrill of the U. S. Navy. Future volumes will treat other phases of missile design which include "Aerodynamics, Propulsion, Structure," "Armament, Launching, Range Testing," "Operations Research, System Engineering" and "Space Flight."

The guiding philosophy behind this book is summarized best by quoting from the preface: "The purpose . . . is to give a

basis for instruction to graduate students, professional engineers, and technical officers of the armed services so that they can become well grounded in the technology of guided missiles. An engineer who absorbs only this material will not be ready at once to commence the design of a guided missile or of its components." With this as its objective, the book performs quite ably. It gathers in one place the multitudinous and varied subjects that ultimately must be used to form a guided missile system.

Each chapter covers one particular topic; for example, the earth and its environs, transmission of radio waves, infrared, servo theory, analysis of flight paths and bandwidth studies, to cite only a few. The coverage is sufficient to instill an awareness of the applicability of the subject to guided missiles, but no chapter is complete enough to allow one to become an expert in the particular field; indeed, the best that can be hoped for is the arousing of interest to the point that the reader will obtain a more detailed treatment of the subject in question.

An engineer experienced in servomechanisms design may wish to skip Chapter 7 (on servo system theory), for it probably contains no new ideas for him (bear in mind that this was not the intent of the book in the first place). On the other hand, this chapter will prove informative to a physicist whose major field is electromagnetic propagation and who has never read a book on servo theory. The servo engineer will be interested in the bandwidth studies (Chapter 18), which represent concepts with which he is familiar, but which are extended into system considerations. It is this type of usefulness which pervades the book.

Certain chapters represent a summary of subjects which, it is believed, have not been compiled previously outside of classified literature. Prominent among these are Chapter 8 (tactical considerations), Chapter 12 (analysis of flight paths), Chapter 13 (prelaunch and launch), and Chapter 20 (system concept).

The space devoted to certain topics may be questioned in view of the stated purpose of the book. For example, in Chapter 7 (servo system theory), sixty pages are devoted to servo theory; the same purpose might be served by presenting only statements of fact and conclusions, rather than complete derivations, and referring the reader to a text on servo fundamentals.

On the other hand, Chapter 10 (detection and information gathering) disposes of the whole field of microwave components by stating that "there is little in the design of r-f components which is peculiar to the field of missile guidance." Here, a prior knowledge is presupposed and the object of the author is simply to reacquaint the reader with basic facts. The latter course seems the better approach.

The principal topic of the book, missile guidance, is covered largely in Chapter 1 (fundamental problems of missile guidance); Chapter 2 (prior developments); Chapter 8 (tactical considerations); and Chapter 16 (missile guidance systems). The material is discussed quite thoroughly and is well illustrated with specific examples of surface-to-surface, surface-to-air, air-to-surface and air-to-air missiles. By

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ELECTRONIC SYSTEMS ENGINEER (Field Service)
Liaison with associate contractors and government agencies on inertial guidance system project. Must be thoroughly familiar with matters relating to digital and analog computers, power supplies, environmental conditions, housing and test facilities and test equipment.

FIELD EVALUATION ENGINEER
Perform overall planning functions for field evaluation of missile guidance systems. Direct activities in scheduling the field operations. Liaison with field test site agencies and formulating overall operating procedures at test site on missile project.

MECHANICAL DESIGN ENGINEER
Perform mechanical design of airborne instrumentation and transducers required for field evaluation of missile guidance systems. Responsible for packaging and mounting equipments.

FUNCTIONAL ENGINEERS—MISSILE SYSTEMS
Develop inertial guidance systems including gyro, accelerometers, integrators, servo systems and computers. Analyze functional problems arising during development and evaluation of said system.

OPERATIONAL EVALUATION ENGINEER
Perform engineering studies and analysis of techniques for evaluating performance of missile guidance systems and its components including gyros, accelerometers, digital computers.

PLATFORM ENGINEER
Conduct investigation of a theoretical nature relating to gyros or inertial platforms including design of closed loop control equipment pertaining to the above.

GYRO DEVELOPMENT ENGINEER
Develop precision gyro systems including mechanical problems such as lubrication, temperature controls, hydrostatics and vibration and electronic work on accelerometers, amplifiers, torquing circuits and electrical pickups.

OPERATIONAL ANALYSIS ENGINEER
Development work on evaluation of inertial guidance systems including in-plant and flight analysis of gyro systems. Development of measuring devices for precise determination of in-flight velocity, acceleration, altitude and position information.

RELIABILITY ENGINEER
Develop methods for evaluation of accuracy, reliability and operational suitability of missile guidance systems.

SYSTEMS EVALUATION (MISSILE GUIDANCE)
Perform functional engineering studies and design of inertial guidance systems, determine system and component requirements and performance, conduct system and component dynamic studies and simulation, perform error analysis.

PROJECT ENGINEER—PRODUCTION TEST EQUIPMENT
Administer and technically direct the program of design, development and manufacture of test equipment for production use in the manufacture, inspection, test and reliability control of highly complex electronic, electro-mechanical and gyroscopic equipment required for missile application.

GROUND EQUIPMENT ENGINEER
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To plan, conduct and report upon development studies of finishes, materials and processes, which will be incorporated into the design of electromechanical and electronic components and systems.

OPERATIONAL ANALYSIS ENGINEER
To plan, conduct and report upon environmental tests of electromechanical and electronic systems. Must be capable of redesigning components or systems to correct any deficiencies encountered during the evaluation program in the computer, servo systems and missile field.

QUALITY CONTROL ENGINEER
Require experience in gyroscopic trouble shooting. Design knowledge of stable elements and some background regarding reliability and failure association for complex guidance systems to be used in missile field. Must have complete knowledge of statistical methods.

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consideration of the several tactical missiles, the authors describe inertial, command, beam riding and command guidance systems and give the reasons for the choice of the guidance system in each case. Although the authors emphasize that their choice for a guidance system is based on a superficial examination of the problem, the inexperienced reader may fail to note this and may consider the authors' choice optimum. For example, with the air-to-air missile, semi-active homing is selected because it permits salvo fire and does not unduly restrict maneuvers of the launching aircraft. A more complete evaluation would bring in other factors, which might eliminate semi-active homing from consideration. However, considering limits required to avoid disclosure of classified information, the authors have provided an excellent résumé on guidance systems for missiles.

Two topics of major importance in the design of guidance systems are reliability and maintainability. These receive limited consideration, but because of their great significance they should receive a more complete treatment even though they lack the glamor of the higher-order differential equation.

Engineers, scientists and military personnel initially embarking on a career in the field of guided missiles will find the book an invaluable source of information. The book provides an organized guide to the many facets of missile systems and it emphasizes the fantastically broad scope of the subject.

The experienced missile engineer should be versed in the major subjects covered. However, he most certainly will discover many facts throughout the text that he has either forgotten or never knew, and the book serves as an excellent reference on missile guidance. A bibliography at the end of most chapters directs the reader to related and advanced treatment of the major topics.

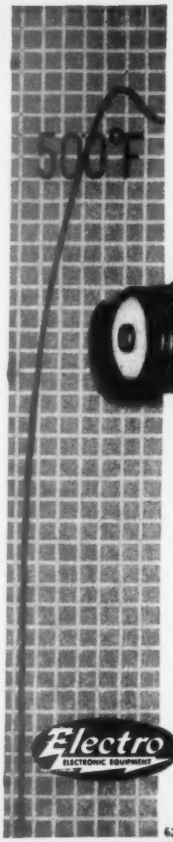
The editor and authors are to be congratulated for assembling in this volume much of the large scientific and industrial effort directed toward the guidance of missiles in flight.

Engineering Analysis, by Stephen H. Crandall, McGraw-Hill Book Co., New York, 1956, ix + 417 pp. $9.50.

Reviewed by JAMES J. KAUZLARICH
Northwestern University

This book is more aptly described by its subtitle: "A Survey of Numerical Procedures." As such, it is a textbook that lays the foundations for further work in engineering analysis by numerical methods. Essentially it complements advanced engineering mathematics from the point of view of analysis of systems that are too difficult to handle by means other than numerical procedures.

Although the book is primarily concerned with numerical procedures, the author has considered as a second objective the construction of a mathematical model for a physical situation. This second objective governs the organization of the book into three general classes of problems: Equilibrium, eigenvalue, and propagation problems.



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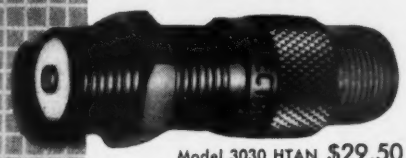

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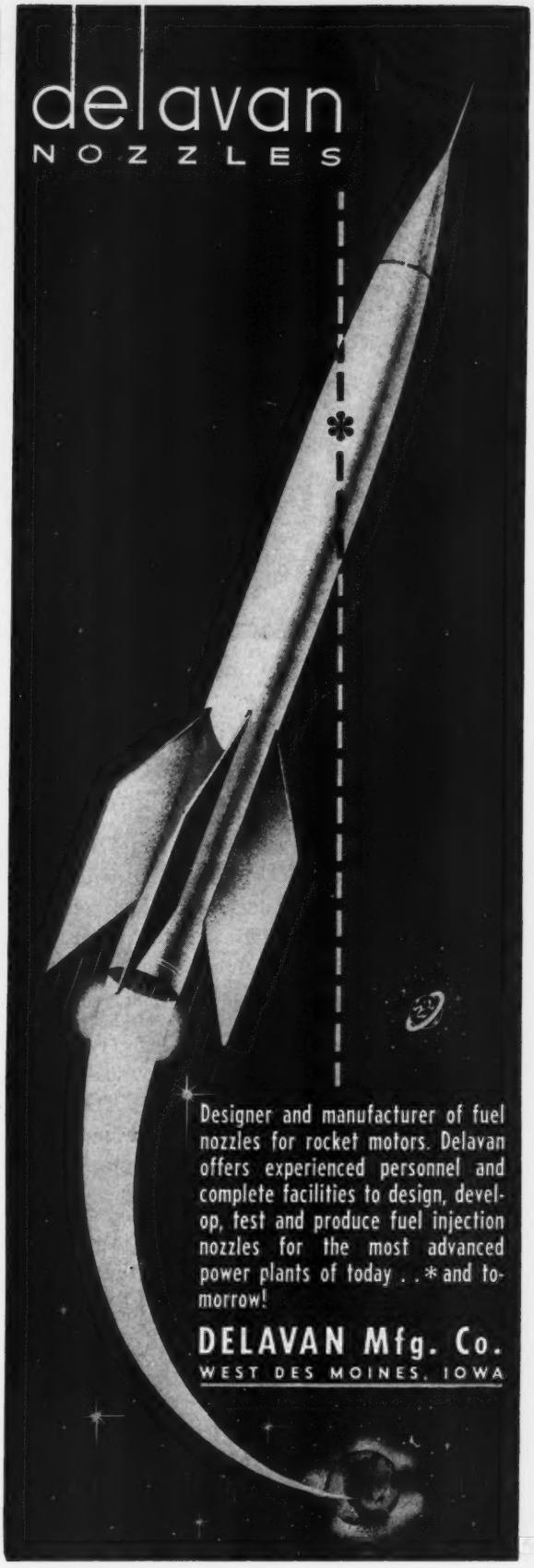

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The book is further subdivided into lumped parameter systems and continuous systems. Thus, of the six chapters, the first three are concerned with the analysis of systems of less difficulty but of the same general type as the last three chapters.

Each chapter follows the same general outline. For example, the following equilibrium problems with lumped parameters are considered in detail: Elastic spring system, d-c network, a-c network, continuous beam and hydraulic network. The mathematical formulation of the problems is given without proof, but sufficient references are listed to augment the discussion. The general mathematical properties of a class of problems are next discussed, and in most of the chapters a discussion of analysis from energy principles is included. The major content of each chapter is concerned with solving the particular class of problems under discussion by numerical methods with specific example solutions for the problems considered in the beginning of each chapter.

In Chapter I the numerical method of successive elimination is discussed from the aspect of a systematic method of computation in order to minimize the number of steps necessary for solution. Other classical procedures such as iteration and relaxation are discussed in detail. The sections on convergence, length of computation, and practical suggestions, augment the practicality of the book. In Chapter II eigenvalue problems for lumped parameter systems are considered, and matrix notation is introduced from the operational aspect of solving problems. Chapter III introduces series methods of solution and trial solutions with undetermined parameters as well as other methods.

In Chapter IV a short section on the extremum method of analysis for continuous systems is presented and the calculus of variations is introduced as a logical approach to obtaining necessary conditions for an extremum to exist. Finite difference methods are also introduced and iteration and relaxation are applied for solution of problems. Of special interest is the method of characteristics presented in Chapter VI used for solution of propagation problems in continuous systems.

This book is particularly suited to the person who desires a descriptive introduction to the subject of numerical analysis of engineering problems. The mature engineer should have little difficulty in understanding the subject matter. The author has presented the general details for the analysis of complex engineering problems, and sufficient references for more detailed study if necessary.

The content of this textbook has been tested for more than six years by being given in a course by the author. The author who is both a mathematician and an engineer is highly qualified as exemplified by his clear presentation of the subject.

Aerodynamics, Propulsion, Structures and Design Practice, by E. A. Bonney, M. J. Zucrow and C. W. Besserer, D. Van Nostrand Co., Princeton, N. J., 1956, xii + 595 pp. $10.

Reviewed by A. E. Noreen
General Electric Company

"Aerodynamics, Propulsion, Structures

and Design Practice," although under one cover, more nearly approaches three separate and not-too-well-integrated books. Unfortunately the three sections do not have a common appeal. Section 1 on aerodynamics and Section 3 on structures and design practice contain a wealth of handbook-type information and current operating practice, much of which would be of value as reference material for engineers, managers and administrators new to the guided missile field. Section 2 on propulsion, occupying 256 of the 595 pages, contains information developed from first principles which can provide understanding of the propulsion system and its design problems. The material in this section, in contrast to Sections 1 and 3, would be quite suitable as a text for the guidance of graduate students as well as a guide to practicing engineers and managers. In a common field this diversity of presentation might produce a well rounded book; however, in this case the fields are adjacent, not coincident, and significant gaps are left in the coverage of aerodynamics and structures and design practice.

Section 1 on aerodynamics, by E. A. Bonney, provides information on nomenclature and procedures associated with the design of the external aerodynamic configuration of a guided missile. The material presented is, for the most part, directly stated without benefit of mathematical proof or reasoned explanation. The lack of explanation or background development and infrequent mention of limitations on stated relationships could encourage application of the contents to situations beyond those justified or intended. The discussion of aerodynamic stability of a missile rises above these limitations. Testing procedures to evaluate aerodynamic performance are described. An extensive bibliography of the unclassified literature on missile aerodynamics is included which should be of considerable use to those desiring a more understandable description of the technology.

Section 2 on propulsion, by M. J. Zucrow, includes a history of missile propulsion systems, general descriptions of the principal configurations, much of the nomenclature associated with propulsion systems for missiles, and the regions of application of the several types of propulsion systems. It contains developments of the major simplified performance parameters for turbojet, ramjet and rocket propulsion systems. These parameters serve as excellent tools for over-all understanding of the functions, capabilities and major design concepts of the respective powerplants.

Since a large portion of the fundamental gas dynamic material included in Section 2 is basic to the subject matter of Section 1, it is unfortunate that the section on propulsion did not precede the section on aerodynamics and that Mr. Bonney did not start with the developed gas dynamics of Professor Zucrow in presenting the aerodynamic characteristics of missiles. The discussion of the ramjet powerplant made excellent use of the few pages devoted to this subject and might well have preceded the discussion of the turbojet afterburner, since a high percentage of this material is applicable to that system.

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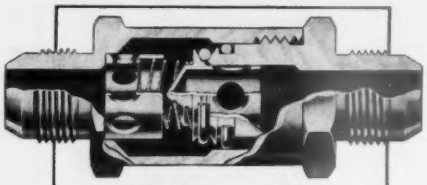

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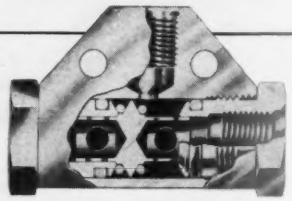

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Section 3, on structures and design practrice, is similar to Section 1 in the type of material included and the manner of presentation. Missing from this section is a description of the procedure for obtaining the basic structural design to which the factors of safety and the design refinements included may be applied. There is an extensive description of materials utilized in guided missile design with many of their properties listed. The text indicated that useful results have been achieved by mathematical analyses of flutter. More than the prosaic presentation of this section would, therefore, seem highly desirable. Design refinements and modifying influences such as environment, packaging and reliability control are discussed. Tests to evaluate designs are described. A very general discussion of heat transfer in electrical equipment is included. The sacrifice of an adequate discussion of guided missile structures for descriptions of detailed design procedures seems unfortunate.

Book Notices

Supersonic Inlet Diffusers and Introduction to Internal Aerodynamics, by Rudolf Hermann, Minneapolis-Honeywell Regulator Company, Minneapolis, 1956, xxi + 378 pp. $16. This book treats supersonic inlet diffuser flow characteristics and is quite unique in that it concentrates on this one field. The problems encountered with diffusers in diverse applications are discussed for specifically spelled-out and differentiated cases. The treatment is mature and includes many graphs which should make this book of considerable help to the design engineer of turbojet and ramjet engines.

Vectors and Tensor Analysis, by Nathaniel Coburn, MacMillan Company, New York, 1955, xii + 341 pp. $7. This is an excellent textbook for the graduate student level in engineering and applied science. Because it covers much material which is not frequently encountered in ordinary texts, it should be of considerable use to the scientist-engineer in his own work. Besides giving the background of vector and tensor analysis, it includes fine applications such as the differential geometry of surfaces, elasticity, viscous fluids, compressible fluids and homogeneous statistical turbulence.

The Mighty Force of Research, by the editors of *Fortune,* McGraw-Hill, New York, 1953–1956, 308 pp. $4. This book is a collection of articles on research which appeared in *Fortune* between January 1953 and August 1955. It deals with such subjects as the status of research, the scientist, solar and atomic power, automation and information theory.

Rocket Propulsion Elements, 2nd edit., by George P. Sutton, John Wiley and Sons, New York, 1956, 483 pp. $10.25. This is the second edition of the well-known book and differs from the original version by having additional and new data, more recent illustrations and three new chapters, including one on heat transfer. A fine introductory book about the practical aspects and design considerations of rocket propulsion.

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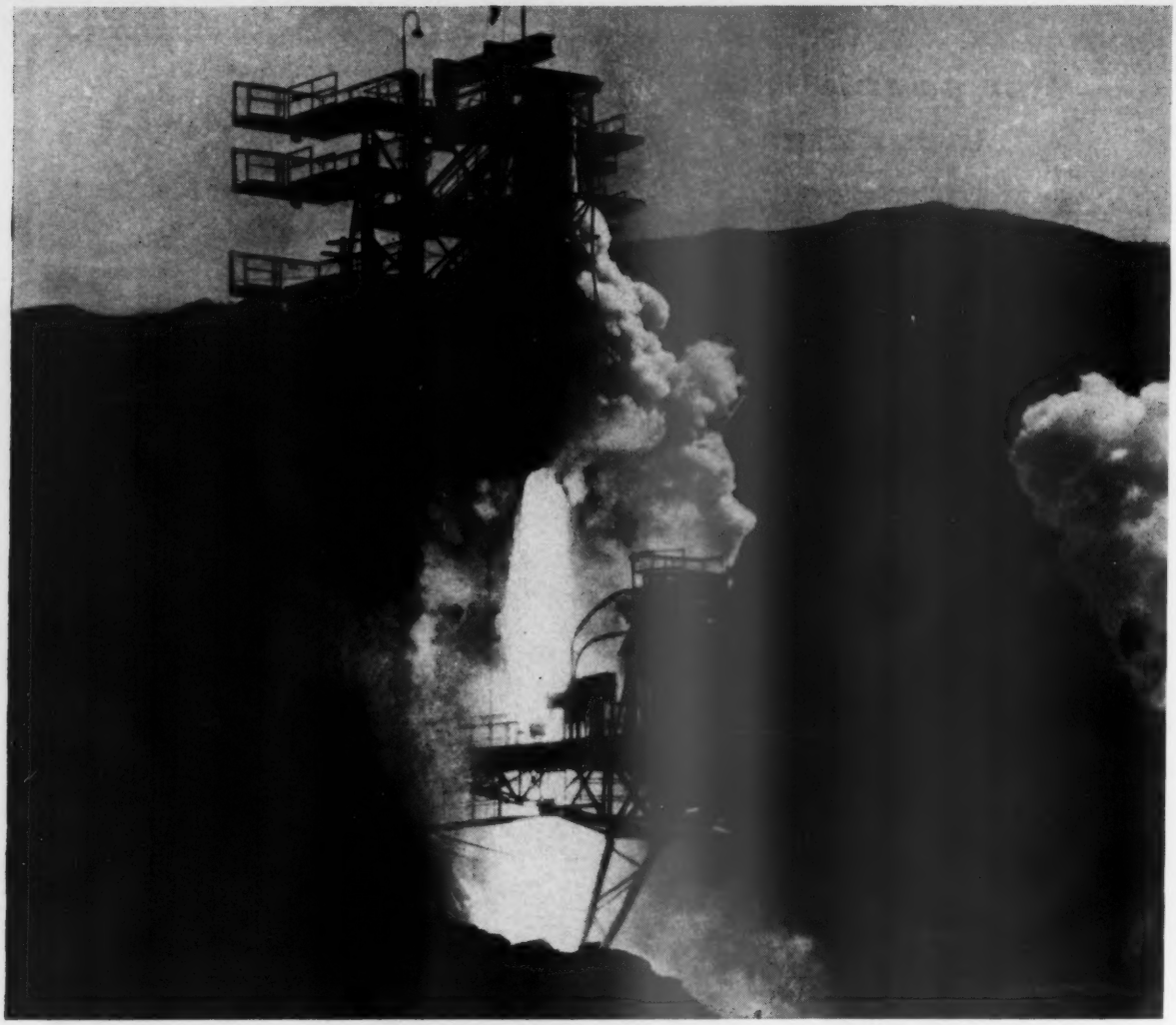

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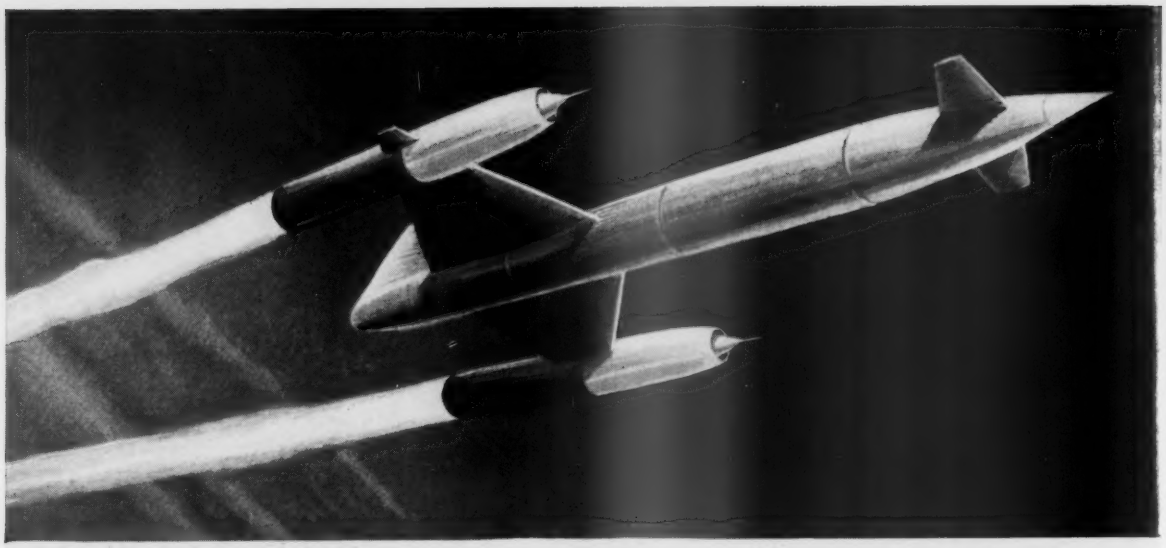

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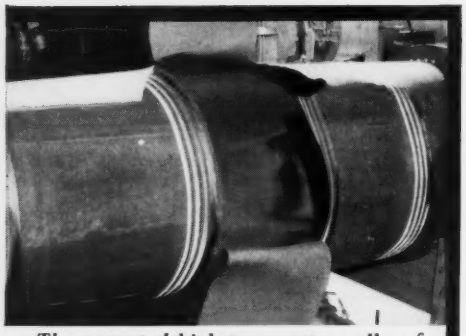

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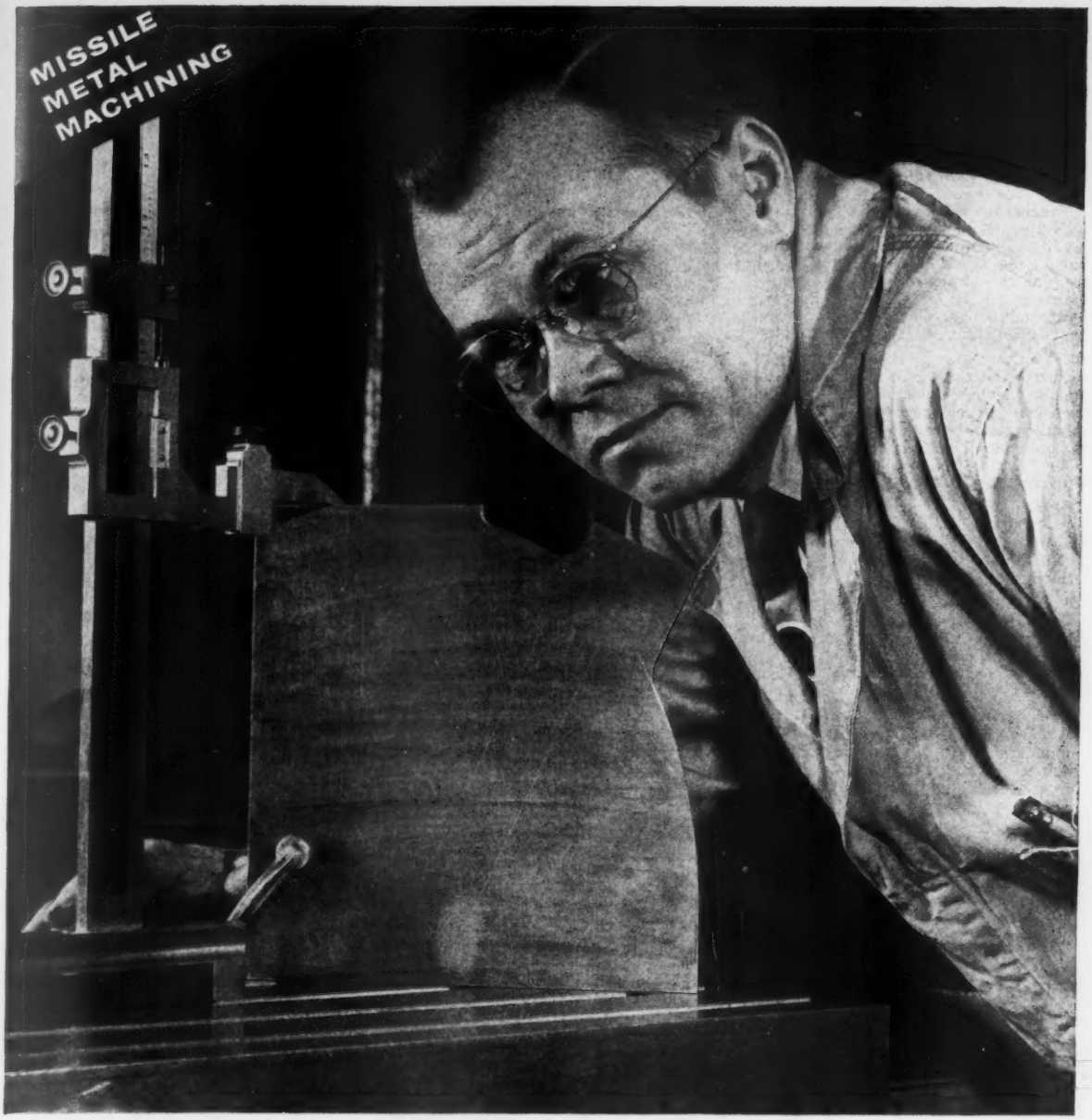

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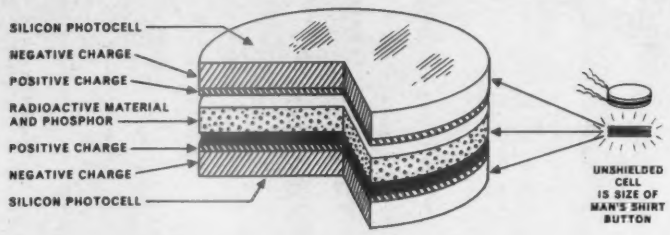

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Accelerometers. Model DDL has ranges of ±0.1 g to ±8 g or up to ±30 g with reduced damping. Model GLH is gold-plated with a range of ±0.1 to ±30 g. Genisco, Inc., 2233 Federal Ave., Los Angeles 64, Calif.

Small TV Camera. Pocket-sized JTV-1 weighs less than 1 lb and measures $1\frac{7}{8}$ × $2\frac{3}{8}$ × $4\frac{1}{2}$ in. Uses F-1.9 lens. Needs only 10 ft-candles of light. Radio Corporation of America, 30 Rockefeller Plaza, New York 20, N. Y.

Floated Gyro. Weighs 8 oz and is for short-time or "aided" automatic guidance systems. Model MIG is 1.75 in. diam and 2.5 in. long. Drift rate is about 0.15 deg per hr. Spinmotor power is 2.5 max. Minneapolis-Honeywell Regulator Co., Aeronautical Div.

Boron Carbon Precistors. Ratings of $\frac{1}{8}$–2 watts, 10 ohms–5 megohms. International Resistance Co., 401 N. Broad St., Philadelphia 8, Pa.

Missile Rate Gyro. Series RF03-0100 has wheel and gimbal system and eliminates points, bearings or loose springs. Weight, 14 oz. Standard pot pickoff is 5000 ohms. Ranges of ±10°/sec to ±800°/sec. Humphrey Inc., 2805 Canon St., San Diego 6, Calif.

High-Temp Servo Components. Ranges of 250–400 F are possible with glass cloth, Teflon or silicone insulation. Black-body surface for maximum heat dissipation. Norden-Ketay Corp., Jericho Turnpike, Commack, L. I., N. Y.

Missile Intercom. For connecting missile stations on a USAF range. Any operator can reach any station instantly. Connecticut Telephone & Electric Corp., Meriden, Conn.

Chopper. Type 605 eliminates RC circuit. Both electrical and mechanical phase lags total 180 deg at 400 cps. Oak Mfg. Co., 1260 Clybourne Ave., Chicago, Ill.

Missile Relay. Rotary-type 206W1 is DPDT and can withstand extremes in temperature, humidity and shock. Used at altitudes up to 80,000 ft; 1.55 in. long with 0.634 diam. Radio Corporation of America, 30 Rockefeller Plaza, New York 20, N. Y.

Linear Servo Accelerometer. Model 4112 is designed for precise measurement or control of linear accelerations over a range of 0.25 cps. Resolves better than 0.001 per cent. Input range from ±0.1 to ±20 g. Donner Scientific Co., Concord, Calif.

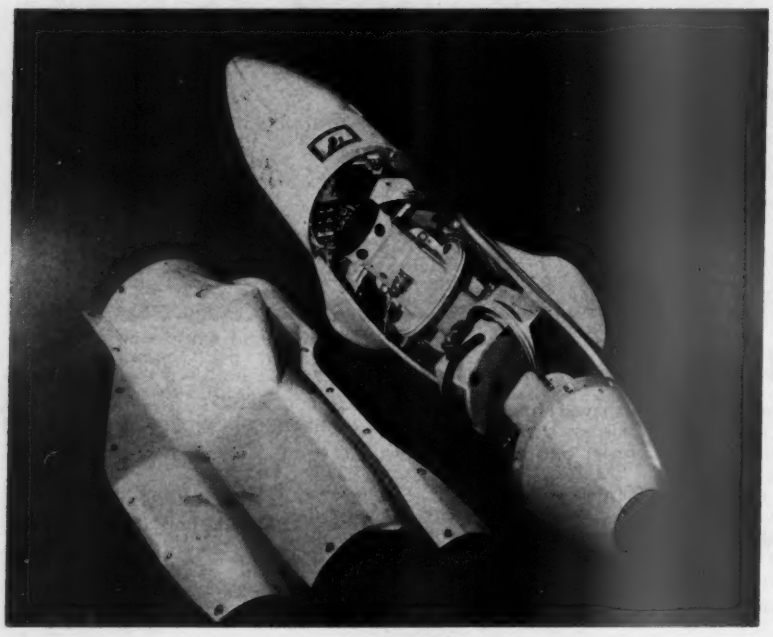
Mechanical

Hi-Pressure Gage. For missiles and launchers. Can take 40 g, vibrations of 5000 cps. Multiple-turn Bourdon helix. Rochester Mfg. Co., Inc., of Calif., 89 Beacon Place, Pasadena, Calif.

Test Stand. For dynamic balancing of large rotating elements such as rocket motors, rotating launchers, flywheels and turbos. Handles parts up to 5000-lb weight, 20,000-lb thrust, 36-in. diam, lenghts to 10 ft and rotation speeds of 10,000 rpm. Aerophysics Development Corp., Box 689, Santa Barbara, Calif.

Spraywelder. Model C-2 sprays aluminum, zinc, copper, nickel, stainless steel, brass, lead or brazing alloys. Powdered metals are first sprayed onto surface and then bonded by oxy-acetylene flame. Wall Colmony Corp., 19345 John R St., Detroit 3, Mich.

Y-Globe Valves. For lox or hydrogen service. Low pressure drop. Normal control or cylinder operated. Pacific Valves Inc., 3201 Walnut Ave., Long Beach 7, Calif.



Photographic Score Keeper

Bell & Howell is manufacturing a new camera pod for the Navy that will be used in evaluating missile performance. Shown above with cover removed to permit removal and loading of its four 16-mm high speed motion picture cameras, the pod is attached to the wing- or fin-tip of a target drone or missile, two pods to a target vehicle. Approaching missiles are always covered by at least two cameras.

Data obtained from the film show missile trajectory, speed, miss distances, etc.

Shuttle Valves. Dead-tight sealing for normal and emergency control systems or preflight check of transducers and pressure switches on missiles and rockets; O-ring seals. James, Pond, and Clark, 4508 Crenshaw Blvd., Los Angeles 43, Calif.

Cutter. Cartridge-actuated, Aerocutter AGX-1800 quickly cuts mechanical parts, tubing or electrical cable. Aerojet-General Corp., Azusa, Calif.

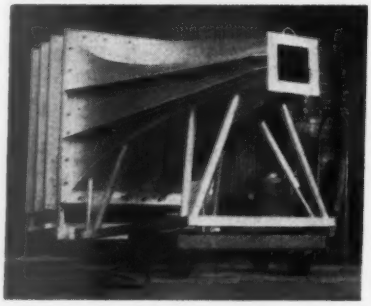
Cutters. Solid propellant powered, Model 106 Riser Cutter severs parachutes. Model 104 Reefer Cutter severs nylon cords. Propellex Chemical Corp., 227 Oakley Place, East Alton, Ill.

Delay Cutter. Reefing Line Cutter has time delay control of 0–10 sec. Cartridge type. **Rocket Catapult.** Standard tube ejector is combined with small rocket located inside catapult tube. Thrust continues after separation. Talco Engineering Co., Hamden, Conn.

Test

Pressure Pickup. Dry strain gage element is isolated from pressurized fluid. For differential use in rockets, turbines, etc. Differentials of ±0.5 psi to ±1000 psi at line pressures up to 2000 psi. Dynamic Instrument Co., Inc., Cambridge, Mass.

Oscillograph. Direct writing, 8-channel model features high speeds. Uses ink, electric or heat sensitive paper. Offner Electronics, Inc., 5320 N. Kedzie Ave., Chicago 25, Ill.



Noise Simulator. Lansing-type loudspeakers generate 151 db noise in range of 50–10,000 cps through an opening 8 × 8 in. Kittell-Lacy, Inc., 10816 E. Fawcett Ave., El Monte, Calif.

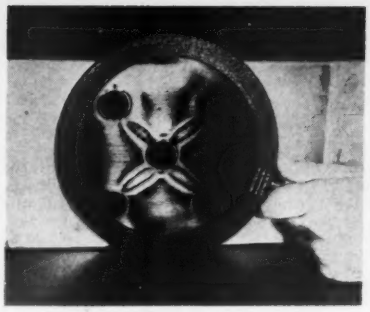
Data Systems. Mach 0.5–1.5 and 1.5–5.0 wind tunnels at United Aircraft Corp., East Hartford, Conn., use analog-to-digital conversion techniques for handling test data. System features strain gage pickups, Bristol potentiometers, Giannini encoders, and an IBM Summary Card Punch. Card punch is fed at the rate of 100 cards per minute. Bristol Co., Waterbury, Conn.

Cine-Interval Camera. Automax 35-mm has cine speed of 16 fps, interval up to 10 fps. Operational at 15 g, 80,000 ft, −70 to 150 F. Traid Corp., 17136 Ventura Blvd., Encino, Calif.

Corrosion Tester. Transistor-type is shock-proof; 9-lb portable Corro-Dex model measures corrosion as low as 0.000001 in. Labline Inc., 3070-82 W. Grand, Chicago 22, Ill.

X-Ray Inspection. Van de Graff accelerator is 1.0 million volts. High Voltage Engineering Corp., Burlington, Mass.

Transistor Furnace. Electric-type BTU Transheat models will maintain alloying, brazing and soldering of semiconductors to within ±0.25 per cent of full scale. BTU



Engineering Co., 440 Somerville Ave., Somerville 43, Mass.

Stress Analysis. Photostress system uses actual full-size unit made of virtually any material. Transparent plastic bonded to part is qualitative and quantitative. Budd Co., 2450 Hunting Park Ave., Philadelphia 32, Pa.

Level Indicator. For liquid metals, sensitive to 1-mm changes in height. Present circuit calls for nonmagnetic wall materials but can be modified for use with magnetic materials. Nuclear Development Corp. of America, 5 New St., White Plains, N. Y.

Liquid Level Switch. Utilizes radioactive material in sensing element for control of fuel level in missiles. Response time is $\frac{1}{20}$ sec and accuracy is ±0.1 in Unit weighs 7 oz. Aeronautical Div., Robertshaw-Fulton Controls Co., Santa Ana Freeway at Euclid Ave., Anaheim, Calif.

Materials

Glass Dispersions. Metal working lubrication is provided by glass in isopropyl alcohol. No. 239 fuses at 1100 F, No. 240 at 1300 F. Acheson Colloids Co., Port Huron, Mich.

Reinforced Plastic. No. 6610 is fire, corrosion resistant plastic Fiberglas. Haveg Industries, Inc., 900 Greenbank Rd., Wilmington 8, Del.

Tubular Stainless. Alloy 17–7 PH is precipitation hardened and is useful at elevated temperatures for structures. Tensile is 200,000 psi. Supplied in annealed form. Carpenter Steel Co., Alloy Tube Div., Union, N. J.

Teflon Tapes. Cementable, glass cloth reinforced and unsupported in widths from ¼ to 12 in. and thicknesses from 2 to 60 mil. Continental-Diamond Fibre Corp., Newark, Del.

Borazon. Cubic boron nitride scratches diamond yet remains hard at temperatures where diamond oxidizes (1600 F). Can withstand temperatures over 3500 F. Specific gravity is 3.45. General Electric Co., Schenectady, N. Y.

Rare Earths. Pure oxides, salts are available. Oxides include: lutetium, gadolinium, samarium, thulium, dysprosium and europium. Jarrell-Ash Co., 26 Farwell St., Newton 60, Mass.

Propellant Catalyst. Burning rate accelerator for ammonium perchlorate composites, double-base solids is based on amino ethyl cellulose perchlorate. Wyandotte Chemicals Corp., Wyandotte, Mich.

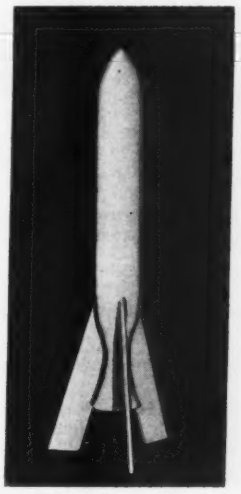
Processes

Flotrusion. Cold flowing of metals into tubular forms can produce nozzles, flares, tapers and other difficult designs. Claude C. Slate Co., 1733 Flower St., Glendale 1, Calif.

Nitrogen Generators. Nitroneal system produces oxygen-free nitrogen from ammonia and air at a cost lower than cylinder nitrogen. Platinum catalyst has indefinite life. Produces 50–10,000 cu ft per hour. Power is 110 v ac. Baker's Instrument Co., 207 Grant Ave., East Newark, N. J.

Unitized Gas Generators. Horsepower outputs range from 0.01 to 150 and output pressures from 15 to 25,000 psi. As an energy source, the systems have high energy/storage ratios with reliability approaching 100 per cent. McCormick Selph Associates, 62 Hollister Airport, Hollister, Calif.

Hydroforming. New company uses process which combines precision in deep drawing and low tool costs. Handles metals from 0.005–⅝ in. from blanks up to 23-in. diam. Metal blank is wrapped around male punch to produce desired part from most metals. Hydroforming Co. of America, 7400 W. Lawrence Ave, Chicago, Ill.



Plastic Rocket. Experimental asbestos-filled phenolic resin can be produced within a 24-hr period. Satisfactory performance is claimed in the 8000–10,000 F range. Haveg Industries, Inc., 900 Greenbank Rd., Wilmington 8, Del.

Product Literature

Low Temperature Apparatus. New 16-page catalog describes lox and nitrogen transportation and storage units, Dewar flasks, etc. Hofman Laboratories, 221 Emmet St., Newark 5, N. J.

Cold Forging. Brochure features process for super alloys, steel and aluminum. Impact Products, Box 7, Orangeville, Ohio.

Combustion Testing. Bulletin 138 illustrates line of manometers, velocity meters, CO and CO_2 indicators. General Scientific Equipment Co., 7516 Limekiln Pike, Philadelphia 50, Pa.

Chromizing. Reprint gives technical data on chromium diffusion into surface of steel parts for corrosion and wear resistance. Chromaloy Corp., 450 Tarrytown Rd., White Plains, N. Y.

Electronics. Brochure outlines missile system testers, mobile training units for missile systems and other electronic systems. Toledo Electronics Div., Kaiser Aircraft & Electronics Corp., Box 437, Toledo 1, Ohio.

New Patents

George F. McLaughlin, *Contributor*

Aircraft reaction propulsion units and installations with means to produce reverse thrust (2,780,058). R. D. Beale, D. H. J. Manningham and B. C. J. Stevenson, Allestree, England, assignors to Rolls-Royce, Ltd.

An auxiliary ducting near the exhaust port is inclined forward where it opens to atmosphere, allowing the gas flow to produce a braking effect when a valve is operated to divert the flow.

Jet direction control device (2,780,059). Willy A. Fiedler, Oxnard, Calif.

The leading edge of a control means is disposed within an annular cavity formed adjacent to the discharge end which opens toward the rear of the body. The cavity has a curved surface for reversing the gas flow during operation of the control.

Jet engine burner construction (2,780,062). Hillard E. Barrett and Wm. F. Payne, Cedar Grove, N. J., assignors to Curtiss-Wright Corp.

Combustible mixture flows over both sidewalls of an open-sided channel in the combustion chamber. The channel extends from (and opens into) the pilot burner tube.

Convertible aircraft with jet-driven rotor (2,780,423). Herbert A. De Cenzo, Arcadia, Calif.

Blade mounting includes a lower tubular section carried by the fuselage, telescoping into the upper section carrying the rotor. Propulsion unit on the blade has a control part and a flap shiftable on the blade. Turning of the rotor causes oscillation of the flap.

Airplane for vertical take-off in horizontal attitude (2,780,424). Nathan C. Price, Hollywood, Calif., assignor to Lockheed Aircraft Corp.

Ducted compressor-ramjet units at the wing tips, and a propulsive nozzle with a variable area exit. Units may be pivoted between positions where their nozzles face aft and downwardly.

Variable configuration jet inlet (2,780,913). Oran W. Nicks, Inglewood, Calif., assignor to North American Aviation.

Leading lip of an air inlet cowl is continuously varied in shape from a sharp edge at high speed flight to a curved edge at low speeds. When the lip is sharp edged, it provides low drag and good pressure recovery at high speeds; when round edged, it provides smooth fluid flow with no separation.

Apparatus for mounting solid propellant grains in a rocket motor (2,781,633). Wm. L. Rogers and Robert L. Noland, Duarte, Calif., assignors to Aerojet-General Corp.

Firing chamber with front, intermediate and rear traps mounted on longitudinal rods supporting solid propellant grains. Adjacent traps are clamped against the respective ends of grains by members threaded on the rods.

Compressor flow control means (2,781,634). Vincent Moore, Glen Rock, N. J., assignor to Curtiss-Wright Corp.

Gas turbine with a duct communicating with the compressor to bleed off air into the surrounding atmosphere. The duct discharge area may be varied so that air bleed is maximum when the duct nozzle is fully open; when closed, all compressor air contributing to thrust is supplied to the combustion chamber.

Low emissivity coatings for metal surfaces (2,781,636). E. A. Brandes and R. B. Waterhouse, Windsor, England, assignors to Fulmer Research Institute, Ltd.

Coatings applied to the internal surface of a gas turbine flame tube for reduction of heat transference. First coat is vitreous enamel, and the second a coating prepared from a refractory material of fused silica, stabilized zirconia, alumina, mineral cordierite magnesia and ceria, prepared in the form of milled particles, with a binder and a wetting agent added.

Explosion initiating device (2,779,284). Ernest M. Kane, Oxnard, Calif.

Device for selectively exploding a substance within a chamber. Openings in a body member communicating with the chamber are sealed by diaphragms. Safety means prevent rupture of one diaphragm which is adapted to rupture at a lower pressure than the other diaphragms.

Propellant powder and process for making same (2,779,288). Joseph Cohen and Eli D. Besser, China Lake, Calif.

Process comprises immersing a nitrocellulose-containing powder grain in a 2:1 water-ethanol solution containing 10 per cent (by weight) of ammonium sulfide, rinsing the grain, and immersing it in glycerin for one to two hours.

Gas turbine engine with hydraulic thrust balancing (2,779,531). John B. Wheatley, Indianapolis, Ind., assignor to General Motors Corp.

An expandable chamber with relatively moving parts is coupled to the rotor and stator for transmission of thrust axially of the motor. Rotation of the rotor develops an end thrust to reduce the load on the thrust bearing.

Control system for afterburner gas turbine engine (2,780,054). Richard J. Coar and Wm. H. Brown, Manchester, Conn., assignors to United Aircraft Corp.

Ignition means responsive to fuel pressure being supplied to an afterburner. A variable area nozzle on the afterburner is controlled to prevent the ignition operation.

Igniter control for engines (2,780,055). Carlton W. Bristol, Glastonbury, Conn., assignor to United Aircraft Corp.

A piston actuated directly by the fuel supplied to an afterburner closes a valve controlling the flow of additional fuel into the engine.

Jet-nozzle arrangement with outlet-area varying means (2,780,056). R. H. Colley, Derby, England, assignor to Rolls-Royce, Ltd.

Even-numbered set of nozzles extending axially with the jet pipe and pivoted to the pipe at their upstream edges. Operation of bevel gears connected to each intermediate nozzle causes a nut to travel along a screw to pivot the nozzle.

Locks for jet thrust reversers (2,780,057). Harry Stavert, Seattle, Wash., assignor to Boeing Airplane Co.

Jet deflector flap swingable outward and rearwardly from a retracted into a projected position transverse to the jet stream and to the relative airstream. A self-lock holds the flap in its limit position.

Helicopter blades and thrust augmenters therefor (2,782,861). Constantin Paul Lent, New York, N. Y.

Rocket engines attached to the outer tips of blades mounted in a rotating armature. Thrust is varied by longitudinal movement of a central core within the exhaust nozzle of each engine.

Aircraft engine installation (2,783,003). Wm. P. Ralston and Richard F. Boehme, Los Angeles, Calif., assignors to Lockheed Aircraft Corp.

Doors mounted at the rear of the fuselage, and hinged along the top, may be opened for the reception or withdrawal of a jet engine. Tracks inside the body, and rollers mounted on the sides of the engine, allow the engine to be moved in or out of the fuselage.

Aircraft launching and landing device (2,783,005). Ernest M. Kane, Oxnard, Calif.

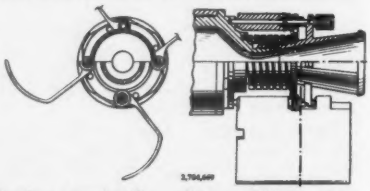
Ground vehicle with a cradle for supporting an aircraft. A curved deflector on the body of the cradle directs air flow upward against the underside of the aircraft as the cradle is moved along a track at a speed equal to that of the airplane in landing or take-off attitude.

Acoustical boundary layer control for aerodynamic bodies (2,783,008). Albert G. Bodine, Jr., Van Nuys, Calif.

Control of the shock front in a layer of air adjacent to an external surface of an aerodynamic body at sonic speed. A sound wave attenuator in the body has a portion extending to the outer surface and connecting with the air layer. The shock front contains acoustic components of frequencies determined by the aerodynamic characteristics of the body.

Propellant composition (2,783,138). John W. Parsons, Pasadena, Calif., assignor to Aerojet-General Corp.

Composition consists of about 50 per cent ammonium perchlorate, with a thermoplastic mixture comprising about 50 per cent trinitrotoluene, 25 per cent SAE No. 10 oil, and 25 per cent asphalt.

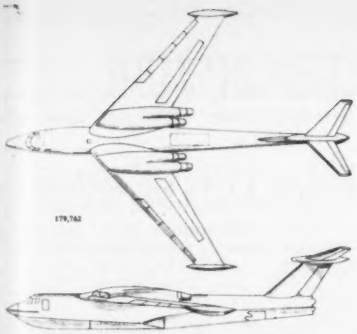


Rocket projectile with stabilizer fins (2,784,669). Robert A. Wallisellen and Wilhelm Niederer, Horgen, Switzerland, assignors to Machine Tool Works Oerlikon, Administration Co.

Gear pinions and a toothed crown, when rotated by expansion of a helical spring after launching, rotate pivots arranged parallel to the projectile axis and simultaneously unfold fins fixed for rotation on each side.

Electrical navigation apparatus (2,784,908). John W. Gray, Wm. D. Green, Jr., and David Sayre, Boston, Mass., assignors to the War Department.

Voltage in an aircraft producing angular displacement proportional to air speed. Voltage is resolved into N-S and E-W voltage components. Voltage corresponding to an assumed wind component is added to the corresponding coordinate component voltage. The magnitude of the correcting voltage may be controlled in accordance with time elapsed from a given starting time.



Airplane [design] (179,762). Robert L. Cox, Jr., Robert L. Hart, Charles J. Koch and John D. Pierson, Glenarm, Md., assignors to The Glenn L. Martin Co.

This design patent, applied for in 1955, covers the configuration known as the XP6M-1 "Sea Master" 4-jet engined mine layer flying boat.

Variable-incidence sweptback wing for aircraft (2,783,956). R. A. Harriss, Wharton, England, assignor to The British Electric Co.

Lifting surface for supersonic aircraft. A trunnion attached to the wing has a sweptback pivot axis passing in plan view between the extreme centroid of pressure positions encountered at different Mach numbers, altitudes and angles of incidence, and through the root section adjacent its maximum thickness. Controls permit adjustment of the surface about the pivot.

Target for projectiles (2,784,000). Luther G. Simjian, Greenwich, Conn., assignor to the Reflectone Corp.

Spaced strips parallel to each other so as to present a barrier to a missile, and tuned to vibrate at characteristic frequencies. Strips are arranged in a predetermined pattern whereby the reproduction of a frequency denotes the position of impact of the missile. A frequency discriminator connected to a microphone produces a signal whose amplitude is proportional to the frequency received.

Parts for machinery (2,783,966). Emil Sorensen, Augsburg, Germany, assignor to Machienfabrik Augsburg-Nurnberg A.G.

Vane, for use in hot gas turbines, formed entirely of ceramic material. The blade is resistant to high temperatures and to wide variations of temperature. The root, of a different ceramic, has greater mechanical strength and stability than the blade.

Ceramic machine parts (2,783,967). H. E. Scharf, R. W. Schmucker and W. Richter, Augsburg, Germany, assignors to Machienfabrik Augsburg-Nurnberg A.G.

Turbine blade of fired ceramic. The vane and root are mounted in a metal rotor having a surface layer of glaze on the root part only. A second surface layer of glaze, of less thickness than the first, effects gradual diminution of glaze thickness, the coefficient of thermal expansion of glaze being less than that of the ceramic material.

Vortical flow gas turbine with centrifugal fuel injection (2,784,551). Henning Karlby and Martin Lessen, Bellefonte, Pa., assignors one-sixth to Orin M. Raphael and one-sixth to George E. Zilliac.

Fuel is injected centrifugally into the combustion chamber to mix with compressed gases from the compressor. Combustion gases move through the chamber in a vortical pattern about the axis of the rotor, giving rotational movement to the turbine as it passes through.

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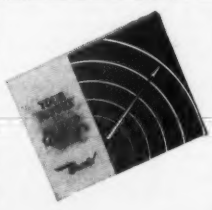

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Technical Literature Digest

M. H. Smith, *Associate Editor*, and M. H. Fisher, *Contributor*
The James Forrestal Research Center, Princeton University

Jet Propulsion Engines

Effect on Mach Number on Over-All Performance of Single Stage Axial Flow Compressor Designed for High Pressure Ratio, by Charles H. Voit, Donald C. Guentert and James F. Dugan, *NACA RM* E50D26, July 1950, 19 pp. (Declassified from Confidential by authority of *NACA Res. Abstracts* 109, Nov. 20, 1956).

Some Aspects of Turbojet Performance Calculation at High Flight Mach Numbers, by J. R. Palmer, *Aircraft Engng.*, vol. XXVIII, Nov. 1956, p. 376.

The Supercharged-and-Intercooled Free-Piston-and-Turbine Compound Engine—A Cycle Analysis, by A. L. London, *Trans. ASME*, vol. 78, Nov. 1956, pp. 1757–1764.

Supersonic Flight: Propulsion, by A. V. Cleaver, *J. Roy. Aeron. Soc.*, vol. 60, Nov. 1956, pp. 705–711.

Rocket Propulsion Engines

Dynamic Stability of Rockets Powerplants Using Liquid Propellants, by Rudolf H. Reichel, *Aero Digest*, vol. 73, no. 5, Nov. 1956, pp. 20–32.

Development of a Reinforced Plastic Head for Jato, 3.5-DS-5700, X220 (Deacon), by P. R. Morgan and C. R. Gottschall, Part I of a series of reports on Research and Development of Reinforced Plastic Components, *Allegany Ballistics Lab., Hercules Powder Co., Cumberland, Maryland*, April 1956, 44 pp. (Report ABL/X-12).

New Rocket Fabrication Method, *Missiles and Rockets*, vol. 1, no. 2, Nov. 1956, p. 59.

British Liquid Rocket Valves, *Missiles and Rockets*, vol. 1, no. 2, Nov. 1956, p. 60.

NACA Boosts Rocket Research, *Missiles and Rockets*, vol. 1, no. 2, Nov. 1956, pp. 82, 84, 86, 88.

Heat Transfer and Fluid Flow

A Correlation between the Dynamic Properties of a Pair of Impinging Streams and the Uniformity of Mixture Ratio Distribution in the Resulting Spray, by Jack H. Rupe, *California Institute Tech., Jet Propulsion Lab., Progress Rep.* 20-209, March 1956, 14 pp.

A Theory for Stability and Buzz Pulsation Amplitude in Ram Jets and Experimental Investigation Including Scale Effects, by Robert L. Trimpi, *NACA Report* 1265, 1956, 24 pp.

Comparison of Pressure-Loss Characteristics of Several Tail-Cone Air-Induction Systems for Air-Cooled Gas-Turbine Rotors, by Gordon T. Smith and Arthur N. Curren, *NACA RM* E52K07, Jan. 1953, 52 pp. (Declassified from Confidential by authority of *NACA Res. Abstracts* 109, Nov. 2, 1956, p. 8.)

Use of Mean-Section Boundary-Layer Parameters in Predicting Three-Dimensional Turbine Stator Losses, by Warner L. Stewart, Warren J. Whitney and Robert Y. Wong, *NACA RM* E55L12a, March 1956, 21 pp. (Declassified from Confidential by authority of *NACA Res. Abstracts* 109, Nov. 20, 1956, p. 9.)

Aspects of Internal-Flow-System Design for Helicopter Propulsive Units, by John R. Henry, *NACA RM* L54F29, Sept. 1954, 24 pp. (Declassified from Confidential by authority of *NACA Res. Abstracts* 109, Nov. 20, 1956, p. 14.)

Generalized Thermodynamical Excess Functions for Gases and Liquids, II, by J. O. Hirschfelder, R. J. Buehler, H. A. McGee, Jr., and J. R. Sulton, *Wisconsin University, Naval Res. Lab., Tech. Rep.* WIS-00R-16, Nov. 1956, 19 pp.

The Thermodynamics of Cooled Turbines, by W. R. Hawthorne, *Trans. ASME*, vol. 78, Nov. 1956, Part I, p. 1765, Part II, pp. 1781–1786.

Effect of Turbine-Blade Cooling on Efficiency of a Simple Gas-Turbine Power Plant, by W. M. Robsenow, *Trans. ASME*, vol. 78, Nov. 1956, pp. 1787–1794.

Analysis of the Effect of Blade Cooling on Gas-Turbine Performance, by J. C. Burke, B. L. Buteau and W. M. Robsenow, *Trans. ASME*, vol. 78, Nov. 1956, pp. 1795–1806.

Shock Waves in Chemical Kinetics: Further Studies on the Rate of Dissociation of Molecular Iodine, by Doyle Britton, Norman Davidson, William Oehman and Garry Schott, *J. Chem. Physics*, vol. 25, Nov. 1956, pp. 804–809.

Shock Waves in Chemical Kinetics, Rate of Dissociation of Molecular Bromine, by Doyle Britton and Norman Davidson, *J. Chem Physics*, vol. 25, Nov. 1956, pp. 810–813.

One-Dimensional Inviscid Flow Through a Rocket Nozzle, by R. P. Rastogi and T. P. Pandya, *J. Chem. Physics*, vol. 25, Nov. 1956, pp. 1009–1012.

Laminar Jet Mixing of Two Compressible Fluids with Heat Release, by S. I. Pai, *J. Aeron. Sciences*, vol. 23, Nov. 1956, pp. 1012–1018.

A Review of Heat Transfer Data on the Evaporation of Liquids at Subatmospheric Pressures, by T. D. Patten, *Royal Aircraft Estab. (Great Brit.)*, Apr. 1956, 22 pp. (*Tech. Note* ME. 216).

Heat Transfer from Combustion Products by Forced Convection, by E. G. Jackson and J. K. Kilham, *Industrial Engng. Chem.*, vol. 48, Nov. 1956, pp. 2077–2079.

Combustion

Growth of Disturbances in a Flame-Generated Shear Region, by Perry L. Blackshear, Jr., *NACA TN* 3830, Nov. 1956, 148 pp.

Solution of Laminar Flame Problems by Use of the Analog Computer, by James Broadwell and John R. Sellers, *Wright Air Dev. Center Tech Rep.* 56-290 (*ASTIA AD* 110477), June 1956, 33 pp.

Flow Disturbances Induced Near a Slightly Wavy Contact Surface, or Flame Front, Traversed by a Shock Wave, by G. H. Markstein, *Project Squid Tech. Rep.* CAL-70-P (*ASTIA AD* 108765), Oct. 1956, 4 pp. (available only on microcard).

Testing Rocket Fuzes for Armed Condition, by J. I. Bujes, *NAVORD Rep.* 5312 (*NOTS* 1548), Sept. 1956, 12 pp.

Gaseous Detonations, IX, A Study of the Reaction Zone by Gas Density Measurements, by G. B. Kistiakowsky and P. H. Kydd, *J. Chem. Physics*, vol. 25, Nov. 1956, pp. 824–835.

Turbulent Burning Velocities of Natural Gas-Air Flames with Pipe-Flow Turbulence, by J. Kenneth Richmand, Joseph M. Singer and others, *Bureau of Mines, Dept. of the Interior, Pittsburgh, Penn.*, April 30, 1956, 28 pp. (*Tech Rep.* 1205; *Tech. Note* AFOSR-TN-56-238).

Theoretical Studies on the Thermal Decomposition of Nitric Oxide in a Shock Tube, by Sterge T. Demetriades and Henry Aroeste, *Daniel and Florence Guggenheim Jet Propulsion Center, California Inst. of Tech., Pasadena, Calif.*, June 1956, 39 pp. (*Tech. Rep.* 3, *Tech. Note* AFOSR-TN-56-335).

Research on the Combustion of a Mixed Hydrocarbon, by Jean Rappeneau, *France, Ministere de l'Air, Publications Sci.*, no. 318, 1956, 90 pp. (in French).

A Relation between Burning Velocity and Quenching Distance, by A. E. Potter, Jr., and A. L. Beriad, *NACA TN* 3882, Nov. 1956, 19 pp.

Preliminary Evaluation of a Rotating Flame Stabilizer as a Means of Achieving Higher Heat Release Rates Per Unit of Combustion Chamber Volume, by John H. Grover, Michael G. Kesler and Arch C. Scurlock, *Project Squid Tech. Rep.* ARC-2-P, Oct. 1956, 23 pp. (available only on microcard).

Flame Stabilization in Volatile Fuel Sprays, by H. C. Hottel, Charles P. Marion and W. P. Jensen, *Project Squid Tech. Rep.* MIT-12-P, June 1956, 48 pp. (available only on microcard).

Flame Stabilization in a Boundary Layer, by Hoyt C. Hottel, Tau-Yi Toong and John J. Martin, *Project Squid Tech. Rep.* MIT-13-P, Oct. 1956, 14 pp. (available only on microcard).

A Relaxation Time Model for Free Radical Concentration, by J. Calvin Giddings, *Project Squid Tech. Rep.* WIS-4-P, Aug. 1956, 18 pp. (available only on microcard).

Photographic Studies of Preignition Environment and Flame Initiation in Turboject-Engine Combustors, by David M. Straight and J. Dean Gernon, *NACA RM* E52I11, Feb. 1953, 40 pp. (Declassified by authority of *NACA Res. Abstracts* 108, Nov. 2, 1956, p. 13.)

Stability Limits and Burning Velocities of Laminar Hydrogen-Air Flames at Reduced Pressure, by Burton Fine, *NACA TN* 3833, Nov. 1956, 29 pp.

Fuels, Propellants and Materials

Theoretical Performance of Mixtures of Liquid Ammonia and Hydrazine as Fuel with Liquid Fluorine as Oxidant for Rocket Engines, by Sanford Gordon and Vearl N. Huff, *NACA RM* E53F08, July 1953, 43 pp. (Declassified by authority of *NACA Res. Abstracts* 107, Oct. 9, 1956, p. 13.)

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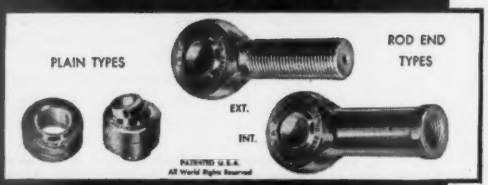

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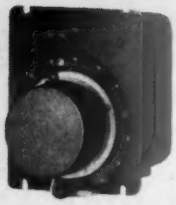

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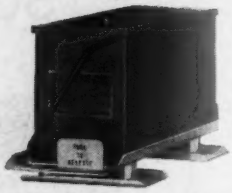

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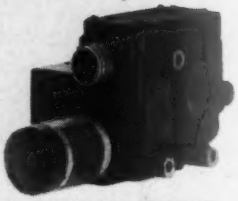

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Mollier Charts for the Products of Combustion of Ammonia and Nitric Acid, by I. Forsten, *Naval Air Rocket Test Sta., Rep.* NARTS 83, April 1956, 12 pp.

Normal Propyl Nitrate Storage Test, by Norman J. Vanderhyde, *AF Flight Test Center, Edwards AFB, TN* AFFTC-TN-56-12, Feb. 1956, 40 pp.

Thermal Stability of Gas Turbine Fuels, by Y. G. Hendrickson and J. T. Guerin, *Calif. Res. Corp., Summary Rep.,* July 1, 1955 to March 31, 1956, 50 pp.

Analytical Procedures for 1,1-Dimethylhydrazine, by William R. McBride and Howard W. Kruse, *Naval Ordnance Test Sta., Rep.* NOTS 14751 *NAVORD Rep.* 5263, May 23, 1956, 20 pp.

Problems and Promises of Free Radical Fuels, *Missiles and Rockets,* vol. 1, Dec. 1956, p. 94.

Ignition Delays and Fluid Properties of Several Fuels and Nitric Acid Oxidants in Temperature Range from 70° to −105°F, by Riley O. Miller, *NACA TN* 3884, Dec. 1956, 32 pp.

Mechanism and Kinetics of the Reaction Between Fuming Nitric Acid and/or Its Decomposition Products and Gaseous Hydrocarbons, *Franklin Inst., Labs. for Res. and Dev., Quart. Prog. Rep.* Q-2452-7, July 1 to Sept. 30, 1956, 21 pp.

Storage and Handling of Unsym-Dimethylhydrazine, *Westavco Chlor-Alkali Div. Food Machinery and Chem. Corp.,* 2nd edit., 16 pp.

Decomposition of Hydrocarbons, by C. V. Berger and H. R. Appell, *Ind. Engng. Chem.,* vol. 48, Sept. 1956, Part I, pp. 1566–1575.

Thermal Conductivity of Fluids. Nitrogen Dioxide in the Liquid Phase, by G. N. Richter and B. H. Sage, *Project Squid Tech. Rep.* CIT-1-P (*ASTIA AD* 104498), July 1956, 27 pp. (available only on microcard).

Methods of Analyzing Polysulfide Perchlorate Propellants, by Charles Ribando, *Picatinny Arsenal Samuel Feltman Ammunition Labs. Tech. Rep.* 2334, Sept. 1956, 21 pp.

Electric Strength of Saturated Hydrocarbon Gases, by J. C. Devins and R. W. Crowe, *J. Chem. Physics,* vol. 25, Nov. 1956, pp. 1053–1058.

Polytechnic Inst. Brooklyn, March 1956, 59 pp. (Tech. Note WADC-TN-56–40).

Development of Iron-Chromium-Manganese Alloys for High-Temperature Applications—Phased 1, Fe-Cr-Mn-N-C Alloys, by C. Hsiao and E. J. Culis, *Crucible Steel Co. of America, Pittsburgh, Penn.,* Quarterly Progress Report no. 2, April–June 1956, July 1, 1956, 37 pp.

The Development of a Protective Coating Resistant to Nitric Acid and Hydrocarbons, by D. F. Siddall, H. L. Cahn and others, Report on Finishes and Materials Preservation, *U. S. Stoneward Co., Akron, Ohio,* Feb. 1956, 93 pp. (Tech. Rep. WADC-TR-54–527).

Contribution to the Study of Combustion of Pyridine Bases, by Jean Ploquin, *France, Ministere de l'Air, Publications Sci. et Techn., Notes Tech.* no. 62, 1956, 21 pp. (in French only).

Theoretical Performance of Some Rocket Propellants Containing Nitrogen and Oxygen, by Riley O. Miller and Paul M. Ordin, *NACA RM* E8A3, May 1948, 53 pp. (Declassified by authority of *NACA Res. Abstracts* 97, Feb. 24, 1956, p. 5.)

Effect of Fuel Volatility Characteristics on Ignition-Energy Requirements in a Turbojet Combustor, by Hampton H.

Foster and David M. Straigh, *NACA RM* E52J21, Jan. 1953, 32 pp. (Declassified by authority of *NACA Res. Abstracts* 108, Nov. 2, 1956, p. 13.)

A Generalized Equation of State for Both Gases and Liquids, I, by J. O. Hirschfelder, R. J. Buehler, H. A. McGee, Jr., and J. R. Sutton, *Wisconsin, University, Naval Res. Lab., Tech. Rep.* WIS-OOR-15, Oct. 1956, 67 pp.

Rocket Engine Propellants, *Missiles and Rockets,* vol. 1, no. 2, Nov. 1956, following p. 134.

Mineral Oils as High Temperature Fluids and Lubricants, by E. Erwin Klaus and Merrell R. Fenske, *U. S. Air Force, Wright Air Dev. Center, USAF WADC TR* 56-254, *AD*-97184, Oct. 1951–Dec. 1955; issued Aug. 1956, 32 pp.

Kinetic Study of the Thermal Decomposition of Ozone, Ph.D. Dissertation by William T. Sutphen, *Stanford Univ.,* May 1955, 115 pp.

A Preliminary Evaluation of Current Stability Tests with an Estimation of Safe Life of Propellants, by Charles Lenchitz and Normal Beach, *Picatinny Arsenal, Samuel Feltman Ammunition Labs. TR* 2348, Sept. 1956, 41 pp.

Combustion of Elemental Boron, Quarterly Summary Report for June through August, 1956, *Experiment Inc. Tech. Mem.* 861, Sept. 1956, 9 pp.

Theoretical Maximum Performance of Liquid Fluorine-Liquid Oxygen Mixtures with JP-4 Fuel as Rocket Propellants, by Sanford Gordon and Roger L. Wilkins, *NACA RM* E54H09, Oct. 1956, 18 pp. (Declassified from Confidential by authority of *NACA Research Abstracts* 107, Oct. 5, 1956 p. 14).

Theoretical Performance of Liquid Hydrazine and Liquid Fluorine as a Rocket Propellant, by Sanford Gordon and Vearl N. Huff, *NACA RM* E53E12, July 1953, 83 pp. (Declassified from Confidential by *NACA Research Abstracts* 107, Oct 5, 1956, p. 13).

Theoretical Performance of Liquid Ammonia, Hydrazine and Mixture of Liquid Ammonia and Hydrazine as Fuels with Liquid Oxygen Bifluoride as Oxidant for Rocket Engines, I, Mixture of Liquid Ammonia and Hydrazine, by Vearl N. Huff and Sanford Gordon, *NACA RM* E51L11, Feb. 1952, 24 pp. (Declassified from Confidential, *NACA Res. Abstracts* 107, Oct. 5, 1956, p. 12.)

Theoretical Performance of Liquid Ammonia, Hydrazine and Mixture of Liquid Ammonia and Hydrazine as Fuels with Liquid Oxygen Bifluoride as Oxidant for Rocket Engines, II, Hydrazine, by Vearl N. Huff and Sanford Gordon, *NACA RM* E52G09, Sept. 1952, 20 pp. (Declassified from Confidential, *NACA Res. Abstracts* 107, Oct. 5, 1956, p. 12.)

Theoretical Performance of Liquid Ammonia, Hydrazine and Mixture of Liquid Ammonia and Hydrazine as Fuels with Liquid Oxygen Bifluoride as Oxidant for Rocket Engines, III, Liquid Ammonia, by Vearl N. Huff and Sanford Gordon, *NACA RM* E52H14, Oct. 1952, 15 pp (Declassified from Confidential, *NACA Res. Abstracts* 107, p. 12.)

Theoretical Performance of Liquid Hydrogen and Liquid Fluorine as a Rocket Propellant, by Sanford Gordon and Vearl N. Huff, *NACA RM* E52L11, Feb. 1952, 28 pp. (Declassified from Confidential, *NACA Res. Abstracts* 107, Oct. 5, 1956, p. 13.)

Theoretical Performance of Liquid Ammonia and Liquid Fluorine as a Rocket Propellant, by Sanford Gordon and Vearl

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N. Huff, *NACA RM* E53A26, March 1953, 25 pp. (Declassified from Confidential, *NACA Res. Abstracts* 107, Oct. 5, 1956, p. 13.)

Theoretical Performance of Lithium and Fluorine as a Rocket Propellant, by Sanford Gordon and Vearl N. Huff, *NACA RM* E51C01, May 1951, 22 pp. (Declassified from Confidential, *NACA Res. Abstracts* 107, Oct. 5, 1956, p. 11.)

Theoretical Performance of Diborane as a Rocket Fuel, by Vearl N. Huff, Clyde S. Calvert, and Virginia C. Erdmann, *NACA RM* E8I17a, Jan. 1949, 31 pp. (Declassified from Confidential, *NACA Res. Abstracts* 107, Oct. 5, 1956, p. 11.)

Use of Closed Bomb Data for Assessment of 60mm Mortar Increment Propellant, by Lester Shulman, *Picatinny Arsenal, Samuel Feltman Ammunition Labs. Tech. Rep.* 2350, Oct. 1956, 27 pp.

Properties of Gaseous and Liquid Mixtures, by Walter K. Tang, *Wisconsin University Naval Res. Lab. Tech. Rep.* WIS-OOR-13, Aug. 1956, 200 pp.

Fundamental Flashback, Blowoff and Yellow Tip Limits of Fuel Gas Air Mixtures, by Joseph Grumer, Margaret E. Harris, and Valeria R. Rowe, *Bureau of Mines Rep. of Investigations* No. 5225, July 1956, 199 pp.

Hydrides and Borohydrides of Light Weight Elements and Related Compounds. *Annual Tech. Rep.* for the Period August 1, 1955– July 31, 1956, *Chicago Univ.*, 46 pp.

How Metallurgy Problems Were Solved in the J47-11, *Aviation Age,* vol. 26, Oct. 1956, p. 40.

Thermal Diffusion in Hydrogen + Boron Trifluoride Mixtures, by C. J. G. Raw and E. Kyle, *Trans. Faraday Soc.*, vol. 52, Sept. 1956, pp. 1216–1218.

The Electrical Conductivity of Liquid and Solid Nitrogen Dioxide, by R. S. Bradley, *Trans. Faraday Soc.*, vol. 52, Sept. 1956, pp. 1255–1259.

Thermal Expansion of Polytetrafluoroethylene (Teflon) from −190° to +300°C, by Richard K. Kirby, *J. Res. Nat. Bur. Stands.*, vol. 57, Aug. 1956, pp. 91–94.

A Method of Calculating the Performance of Liquid Propellant Systems Containing the Species C, H, O, N, F, and One Other Halogen with Tables of Required Thermochemical Properties to 6000°F, by J. S. Martinez and G. W. Elverum, Jr., *Calif. Inst. Tech. Jet Propulsion Lab., Mem.* 20–121, Dec. 1955, 87 pp.

Fluorine Propellant Study, Quarterly Progress Report for Period Ending Aug. 31, 1956, by *North Amer. Aviation Inc., Rocketdyne Div., Rep.* R-334-1, Sept. 1956, 28 pp.

Chemistry of Boron Hydrides and Related Hydrides, by R. W. Parry, R. C. Taylor, T. C. Bissot, D. H. Campbell, A. E. Emery, P. R. Girardot, G. Kodama, D. R. Schultz, S. G. Shore, and J. T. Yoke III, *Wright Air Dev. Center, TR* 56-318 (*ASTIA AD* 97233), Aug. 1956, 174 pp.

Some New Materials for Missile and Power-Plant Applications, by A. V. Levy, *Aircraft Engng.*, vol. 28, Oct. 1956, pp. 357–360.

Effect of Additives on Jet Fuel Stability and Filterability, by A. C. Nixon and H. B. Minor, *Ind. Engng. Chem.*, vol. 48, Oct. 1956, pp. 1909–1916.

Physical Properties of Titanium, II, The Hall Coefficient and Resistivity, by Georgiana W. Scovil, *J. Appl. Phys.*, vol. 27, Oct. 1956, pp. 1196–1198.

On the Kinetic Energy of Molecular Electrons in Compressed Gases, by Anson Solem and Laurens Janse, *J. Chem. Phys.*, vol. 25, Oct. 1956, pp. 686–692.

Application of Cell Theory to Liquid Hydrocarbons, by Robert Simha and Stuart T. Hadden, *J. Chem. Phys.*, vol. 25, Oct. 1956, pp. 702–709.

Instrumentation and Experimental Techniques

The Use of Piezo Gages in Closed Bomb Tests of Solid Propellants, by Arthur S. Rubin and August G. Edwards, *Picatinny Arsenal, Samuel Feltman Ammun. Lab., TR* 2367, Dec. 1956, 39 pp.

Compact, High Capacity Data Recording System, by Engelbert Kirchner, *Aviation Age,* vol. 26, Dec. 1956, Sect. A, pp. 64–69.

A Dynamic Head Probe for Evaluating the Properties of Free Liquid Jets, by Jack H. Rupe, *Calif. Inst. Tech., Jet Propulsion Lab., Prog. Rep.* 20–299, May 1956, 14 pp.

Evaluation of an Image Converter as a High Speed Camera Shutter, by David R. Margetts and Allen E. Wolfe, *Calif. Inst. Tech., Jet Propulsion Lab., Mem.* 20-131, 1956, 24 pp.

Terrestrial Flight, Vehicle Design

The Surface-to-Surface Missile, Today and Yesterday, by F. I. Ordway, *Interavia,* vol. 11, Dec. 1956, pp. 974–977.

Missile Design, the State of the Art, by Pater J. Farmer, *Flight,* vol. 70, Dec. 7, 1956, pp. 885–889.

Missile Testing, *Flight,* vol. 70, Dec. 7, 1956, pp. 890–892.

Guided Missiles, 1956, *Flight,* vol. 70, Dec. 7, 1956, pp. 893–910.

Guided Missiles and Piloted Aircraft Are Technically Alike, by D. L. Putt, *Aviation Age,* vol. 26, Dec. 1956, Sect. A, pp. 20–25.

Stationary Trajectories for a High-Altitude Rocket With Drop-Away Booster, by G. Leitmann, *Astron. Acta,* vol. 2, no. 3, 1956, pp. 119–124.

A Calculus of Variations Solution of Goddard's Problem, by G. Leitmann, *Astron. Acta,* vol. 2, no. 2, 1956, pp. 55–62.

On the Calculation of a Powered Flight of a Long Range Rocket Supervised by an Automatic Pilot, by J. M. J. Kooy, *Astron. Acta,* vol. 1, no. 4. 1956, pp. 191–198.

A Simultaneous Analytical Integration of the Equations of Motion of a Winged Vehicle in Supersonic Gliding Flight, by H. J. Kaeppeler, *Astron. Acta,* vol. 1, no. 4, 1956, pp. 166–170 (in German).

Army Missiles of Tomorrow, *Missiles and Rockets,* vol. 1, Nov. 1956, pp. 34–35.

Army's Role in Guided Missiles, by H. N. Toftoy, *Missiles and Rockets,* vol. 1, Nov. 1956, pp. 36–39.

Army's Missile Arsenal Today, by Patrick W. Powers, *Missiles and Rockets,* vol. 1, Nov. 1956, pp. 40–42.

Prelude to the ICBM, *Missiles and Rockets,* vol. 1, Nov. 1956, p. 43.

Key to Survival: Missile Research and Development, by B. A. Schriever, *Missiles and Rockets,* vol. 1, Dec. 1956, pp. 55–57.

Comprehensive Testing Speeds Missile Development, by L. I. Davis, *Missiles and Rockets,* vol. 1, Dec. 1956, pp. 61–63.

Missile Roles and Missions, *Missiles and Rockets,* vol. 1, Dec. 1956, pp. 70–71.

Space Flight, Astrophysics, Aerophysics

Our Century Will See the Birth of Astronautics, by G. A. Crocco, *Interavia,* vol. 11, Dec. 1956, pp. 948–949.

The IGY Rocket and the Satellite Program, by J. Kaplan, *Interavia,* vol. 11, Dec. 1956, pp. 953–955.

The Artificial Earth Satellite—Past, Present and Future, by S. F. Singer, *Interavia,* vol. 11, Dec. 1956, pp. 956–959.

Instrumental Satellites and Instrumental Comets, by K. A. Ehricke, *Interavia,* vol. 11, Dec. 1956, pp. 960–962.

An Airborne Method of Launching Satellites, by A. C. Robotti, *Interavia,* vol. 11, Dec. 1956, pp. 970–972.

Can Man Reach Distant Celestial Bodies? by J. Ackeret, *Interavia,* vol. 11, Dec. 1956, pp. 989–991.

Space Travel and Future Research Into the Structure of the Universe, by J. M. J. Kooy, *J. Brit. Interplan. Soc.*, vol. 15, Sept.-Oct. 1956, pp. 248–259.

A New Approach to Space Flight, by William O. Davis, *Missiles and Rockets,* vol. 1, Dec. 1956, pp. 64–66.

Navigation in Interplanetary Space, by Peter Castruccio, *Missiles and Rockets,* vol. 1, Dec. 1956, pp. 98-99, 101.

Optimal Transfer Between Circular Orbits About Two Planets, by D. F. Lawden, *Astron. Acta,* vol. 1, No. 2, 1955, pp. 89–100.

Protection of Humans from Heavy Nuclei of Cosmic Radiation in Regions Outside the Atmosphere, by H. J. Schaefer, *Astron. Acta,* vol. 1, no. 2, 1955, pp. 100–109.

Artificial Satellite, Unification and Mechanics (Sidar-Mechanics), by A. Boni, *Astron. Acta,* vol. 1, no. 3, 1955, pp. 120–136.

On the Descent of Winged Orbital Vehicles, by K. A. Ehricke, *Astron. Acta,* vol. 1, no. 3, 1955, pp. 137–155.

Studies of a Minimum Orbital Unmanned Satellite of the Earth (MOUSE). Part I. Geophysical and Astrophysical Applications. Part II. Orbits and Lifetimes of Minimum Satellites, by S. F. Singer, *Astron. Acta,* vol. 1, no. 4, 1955, pp. 171–184; vol. 2, no. 3, 1956, pp. 125–144.

Optimum Launching of a Rocket Into the Orbit About the Earth, by D. F. Lawden, *Astron Acta,* vol. 1, no. 4, 1955, pp. 185–190.

A Suggested Organization of Space Flight Sciences, by D. C. Romick, *Astron. Acta,* vol. 1, no. 4, 1955, pp. 199–208.

Aero-Thermodynamics of Descending Orbital Vehicles, by K. A. Ehricke, *Astron. Acta,* vol. 2, no. 1, 1956, pp. 1–19.

Some Considerations in Regard to the Physiology of Space Flight, by F. A. Hitchcock, *Astron. Acta,* vol. 2, no. 1, 1956, pp. 20–29.

Relativistic Rocket Mechanics, by H. G. L. Krause, *Astron. Acta,* vol. 2, no. 1, 1956, pp. 30–47 (in German).

Relativistic Time Dilitation of an Artificial Satellite, by F. Winterberg, *Astron. Acta,* vol. 2, no. 1, 1956, pp. 25–29 (in German).

The Satelloid, by K. A. Ehricke, *Astron. Acta,* vol. 2, no. 2, 1956, pp. 63–100.

The Visibility of an Earth Satellite, by R. Tousey, *Astron. Acta,* vol. 2, no. 2, 1956, pp. 101–112.

The U. S. Satellite Vehicle Program, by F. L. Ordway III, *Astron. Acta,* vol. 2, no. 3, 1956, pp. 115–118.

Solar Cosmic Rays of February 1956 and Their Propagation Through Interplanetary Space, by P. Meyer, E. N. Parker, and J. A. Simpson, *Phys. Rev.*, vol. 104, Nov. 1956, pp. 768–783.

Satellite Launching from an F-102, by A. C. Robotti, *Missiles and Rockets*, vol. 1, Nov. 1956, pp. 54–56, 58.

International Geophysical Year Earth Satellite Vehicle Program, *Missiles and Rockets*, vol. 1, Nov. 1956, pp. 120–121.

Satellites, by Jorgen Jensen, *Aeron. Engng. Rev.*, vol. 15, Sept. 1956, pp. 44–47.

A **New Theory of the Formation of the F2 Layer,** by T. Yonezawa, *J. Radio Res. Labs. Tokyo, Japan*, vol. 3, Jan. 1956, pp. 1–16.

The Structure of the F2 Layer as Deduced from its Daily Variations, by T. Shimazaki, *J. Radio Res. Labs., Tokyo, Japan*, vol. 3, Jan. 1956, pp. 17–43.

Measurements of the Amplitude Probability Distribution of Atmospheric Noises, by H. Yuhara, T. Ishida, and M. Higashimura, *J. Radio Res. Labs., Tokyo, Japan.* vol. 3, Jan. 1956, pp. 101–108.

Propagation of Electro-Magnetic Waves over the Spherical Earth Across Boundaries Separating Different Earth Media, by K. Furutsu, *J. Radio Res. Labs., Tokyo, Japan*, vol. 2, Oct. 1955, pp. 345–398.

Movement of Irregularities in the E Region (II), by T. Obayashi, *J. Radio Res. Labs., Tokyo, Japan*, vol. 2, Oct. 1955, pp. 413–417.

What the Future Holds for the Earth Satellite, by R. P. Havilland, *Gen. Electric Rev.*, vol. 59, Sept. 1956, pp. 10–16.

Space Navigation Challenges Engineers, by Peter A. Castruccio, *Aviation Week*, vol. 65, Sept. 3, 1956, pp. 82–99.

The IGY Earth Satellite Program, by Hugh Odishaw, *J. Instrum. Soc. Amer.*, vol. 3, Sept. 1956, pp. 298–301.

Astronautical Physiology, by A. E. Slater, *Aeroplane*, vol. 91, Oct. 1956, pp. 522–523.

Perturbations of a Satellite's Orbit Due to the Earth's Oblateness, by Leon Blitzer, Morris Weisfeld, and Albert D. Whellon, *J. Appl. Phys.*, vol. 27, Oct. 1956, pp. 1141–1149.

We Can Build a Moon Rocket Now, by Kurt R. Stehling and Richard Foster, *Missiles and Rockets*, vol. 1, Oct. 1956, pp. 58–60, 62, 64.

One-Stage Rocket for Space, *Aviation Week*, vol. 65, Oct. 1956, p. 34.

Navigation by Satellites, by Lovell Lawrence, Jr., *Missiles and Rockets*, vol. 1, Oct. 1956, pp. 48–52.

Tracking the IGY Satellites, by Henry P. Steier, *Missiles and Rockets*, vol. 1, Oct. 1956, pp. 76–78, 80.

Application of an Artificial Satellite to the Measurement of the General Relativistic "Red Shift," by S. F. Singer, *Phys. Rev.*, vol. 104, Oct. 1, 1956, pp. 11–14.

Building the First Satellite, *Missiles and Rockets*, vol. 1, Oct. 1956, pp. 68–70.

One Orbit out of Twelve "Good" Satellite Average, Martin Says, by James Dailey, *Aviation Week*, vol. 65, Oct. 1956, pp. 30–31.

The Black Sheep System of Forecasting Winds for Long-Range Jet Aircraft, *Air Weather Service, Washington, D. C.*, March 1956, 48 pp. (*Tech. Rep.* 105–139).

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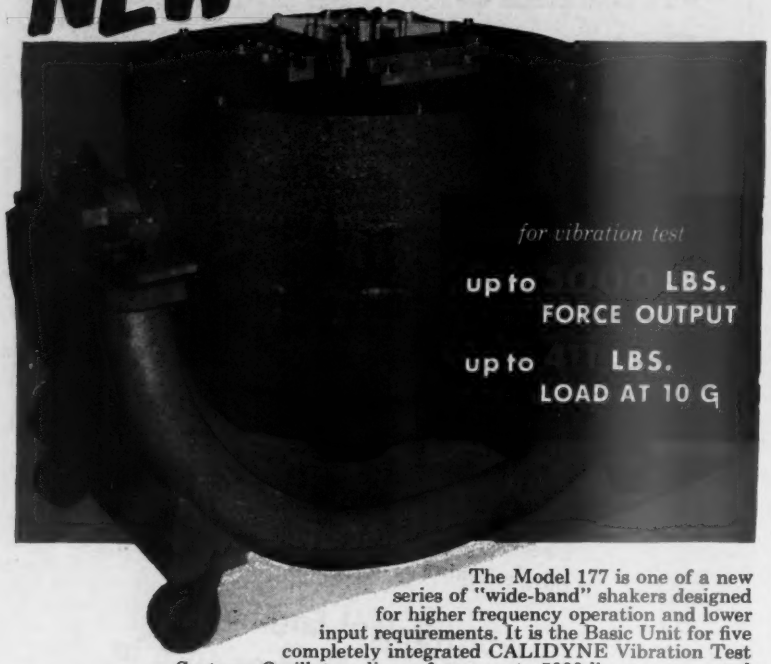

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Liquid Hydrogen as a Rocket Propellant, by Alexis Pastuhov and C. Lincoln Jewett, *Aero Digest*, vol. 73, Sept. 1956, pp. 35–39.

The Selection of Materials for High-Temperature Applications in Aircraft Gas Turbines, *Battelle Mem. Inst. Titanium Metallurgical Lab., TML Report* No. 50, Aug. 17, 1956, 30 pp.

Erosion Protection for Aircraft Components, by J. R. Cuthill and W. N. Harrison, *Wright Air Dev. Center, WADC TR* 56-130, April 1956, 50 pp.

Corrosion Studies in Fuming Nitric Acid, by Edson H. Phelps, Frederick S. Lee, and Raymond B. Robinson, *Wright Air Dev. Center, WADC TR* 55-109, June 1953–April 1954; issued Oct. 1955, 40 pp.

Turbine Disks for Jet Propulsion Units, Part 3, Blade Root Fixing of Turbine Disks for Jet Engine Units, by A. E. Johnson, *Aircraft Engng.*, vol. 28, Oct. 1956, pp. 348–356.

Physical Properties of JP-4 Fuels and Development of Equations for Predicting Fuel System Performance under Two-Phase Flow Conditions, by J. Kelly Gladden, Mario J. Golia, and Henderson C. Ward, *U. S. Air Force Wright Air Dev. Center, USAF WADC TR* 55-422, Part 2, Nov. 1955, 170 pp.

What's Ahead in the Field of Jet Fuels, by Aubrey Keif, *Amer. Aviation*, vol. 20, Oct. 1956, pp. 46–48.

Atomic Energy

The Application of a Fast Neutron Atomic Reactor to an Unconventional Mach 3 Ramjet, by Stanley Owen Smith, *1956 First Award Papers, I.A.S. Student Branch Paper Competition*, New York, Institute of the Aeronautical Sciences, 1956, pp. 77–96.

Series of Lectures on Physics of Ionized Gases (California University, Los Alamos Scientific Laboratory), *Atomic Energy Commission, Rep.* LA-2055, March 1955–June 1956, 1 vol.

Papers Presented at the Technical Briefing Session Held at Idaho Falls, Idaho, Nov. 1–2, 1955 (Boiling Water Reactor Program and Fast Reactor Program), *Atomic Energy Commission*, TID-7506, Part 1, June 1956, 221 pp.

The Physics of Nuclear Reactors, *Brit. J. Appl. Phys., Supp.*, no. 5, July 3–6, 1956, 112 pp.

The Application of Nuclear Energy to Ramjet Propulsion, by H. J. Kaeppeler, *Astron. Acta*, vol. 2, no. 1, 1956, pp. 48–52 (in German).

Stationary Nuclear Reactions in Rockets by E. Sänger, *Astron. Acta*, vol. 1, no. 2, 1955, pp. 61–88 (in German).

On the Possibility of Producing Thermonuclear Reactions in a Gas Discharge, by J. V. Kurchatov, Moscow, 1956 (Russian, pp. 1–20; English, pp. 21–36).

The Possibility of Producing Thermonuclear Reactions in a Gas Discharge, by I. V. Kurchatov, *Soviet J. Atomic Energy*, vol. 1, no. 3, 1956, pp. 359–366 (in English).

What Are Physical Problems of a Controlled Thermonuclear Reactor? by Melvin B. Gottlieb, *Indust. Labs.*, vol. 7, Nov. 1956, pp. 68–69.

Controlled Fusion Research—an Application of the Physics of High Temperature Plasmas, by Richard F. Post, *Revs. Modern Phys.*, vol. 28, July 1956, pp. 338–362.

Power Sources for Space Flight, by S. F. Singer, *Missiles and Rockets*, vol. 1, Dec. 1956, pp. 82–84.

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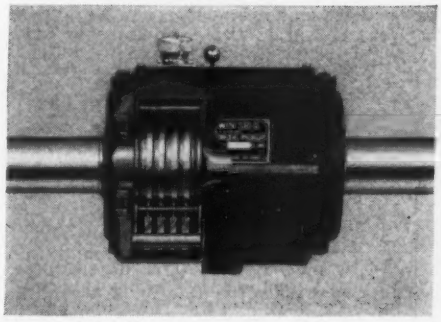

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